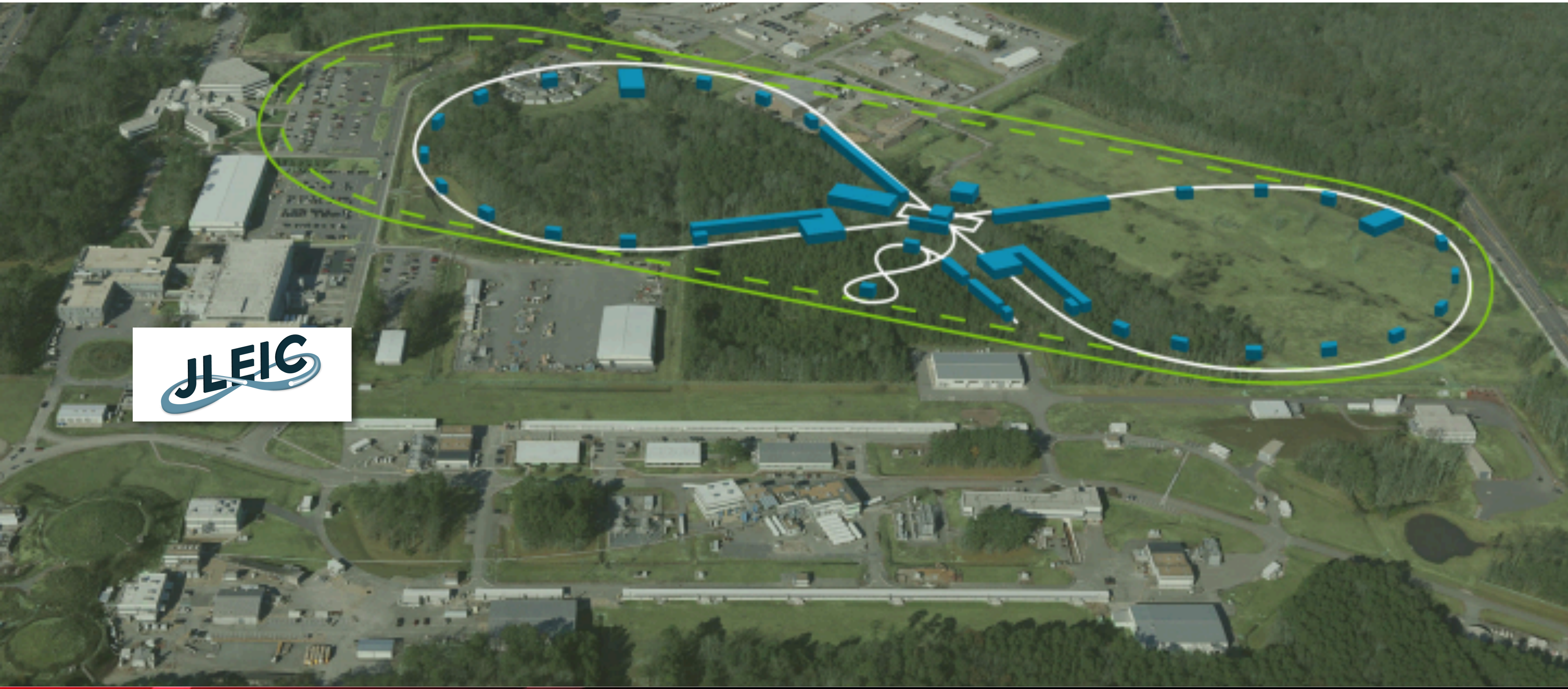
Jefferson Lab Electron-Ion Collider: Physics, Accelerator and Detector



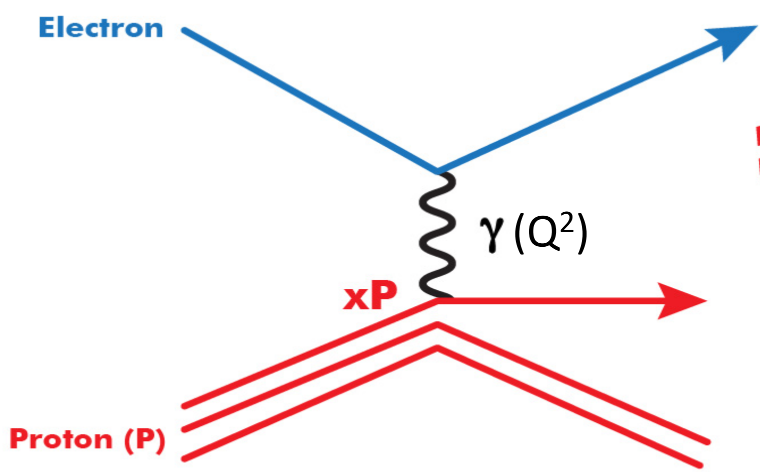
POETIC 7, Philadelphia
November 15, 2016

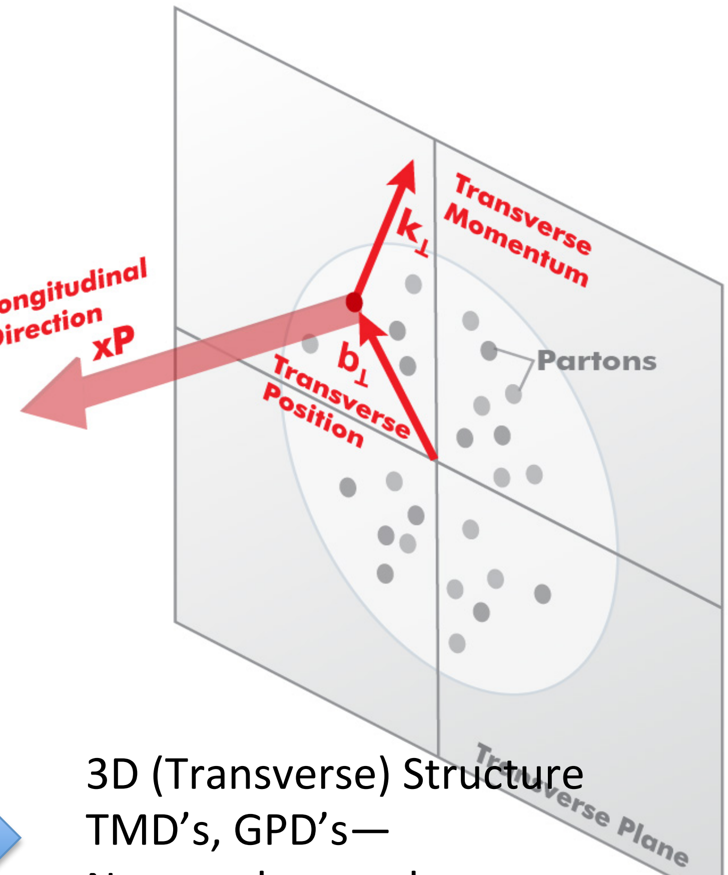
PHYSICS

Introduction

- Advance in theoretical understanding of perturbative quantum chromodynamics (pQCD) ➔
  - Quantitative understanding of DIS processes to be measured has led to ➔
  - Jefferson Lab 12 GeV program
- Understanding of energies of a DIS collider and luminosities required for the full picture of nucleons and nuclei lead to ➔
- Jefferson Lab Electron-Ion Collider (JLEIC) proposal:
  - Use the understanding of high luminosity collider gained at b-factories
  - Optimize the beam energies as well as interaction region + detector design for the measurements required.

Progress in pQCD Theory (~1980-~2010)





Parton Distribution Functions:
Longitudinal only—
No way to interpret nucleon partonic structure in rest frame

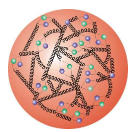
3D (Transverse) Structure
TMD's, GPD's—
Now we know what to measure to understand partonic structure of nucleons

Jefferson Lab 12 GeV program based on this progress.
How do we get the complete picture:
origin of mass, spin, nuclear forces…? EIC !

Where EIC Needs to be in x (nucleon)

Saturation Regime: Needs to be accessed via Ions

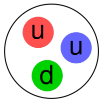
Collective Regime



Many-body Regime

Few-body Regime

(JLab 12)



10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 X (for proton)

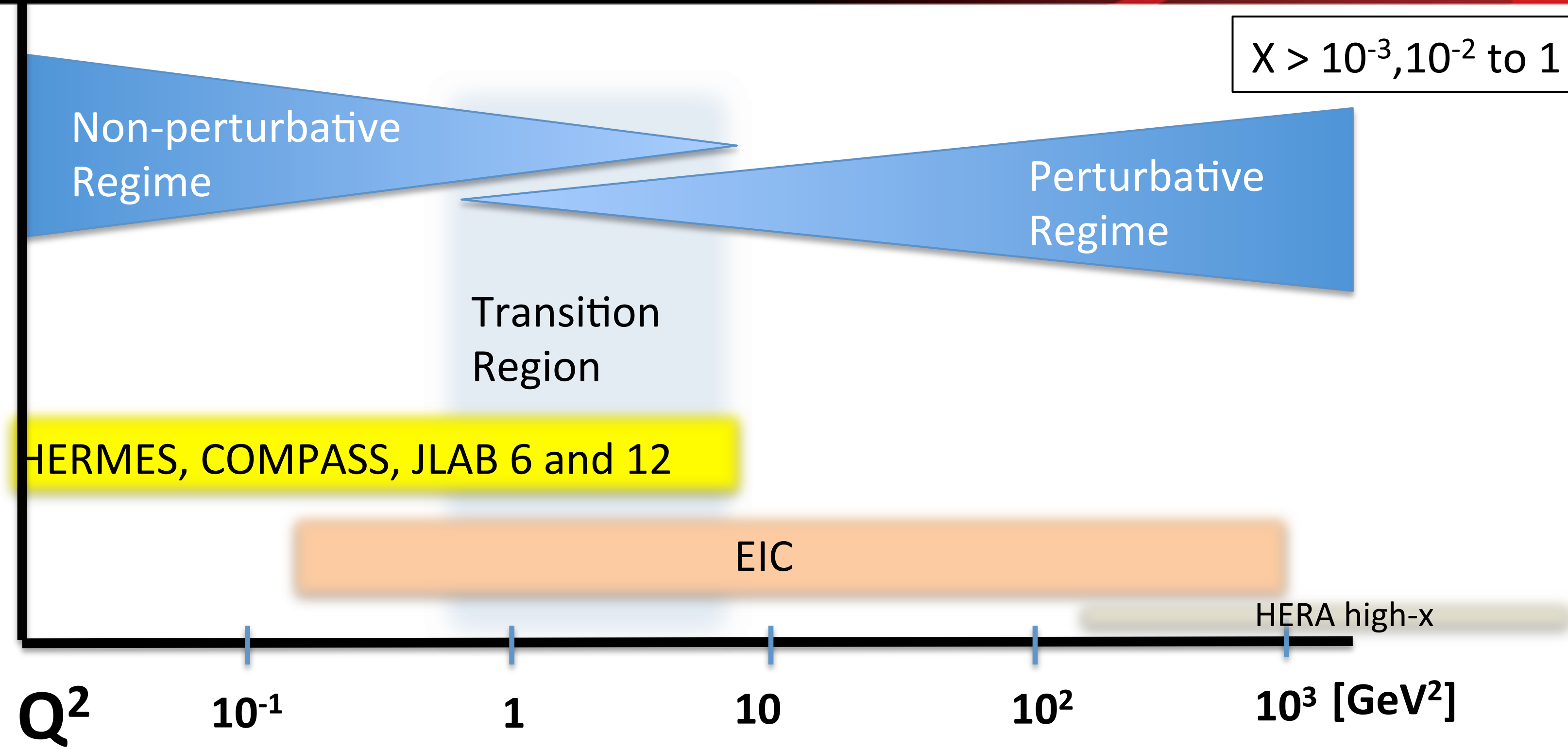
QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

Spin,TMD, GPD…

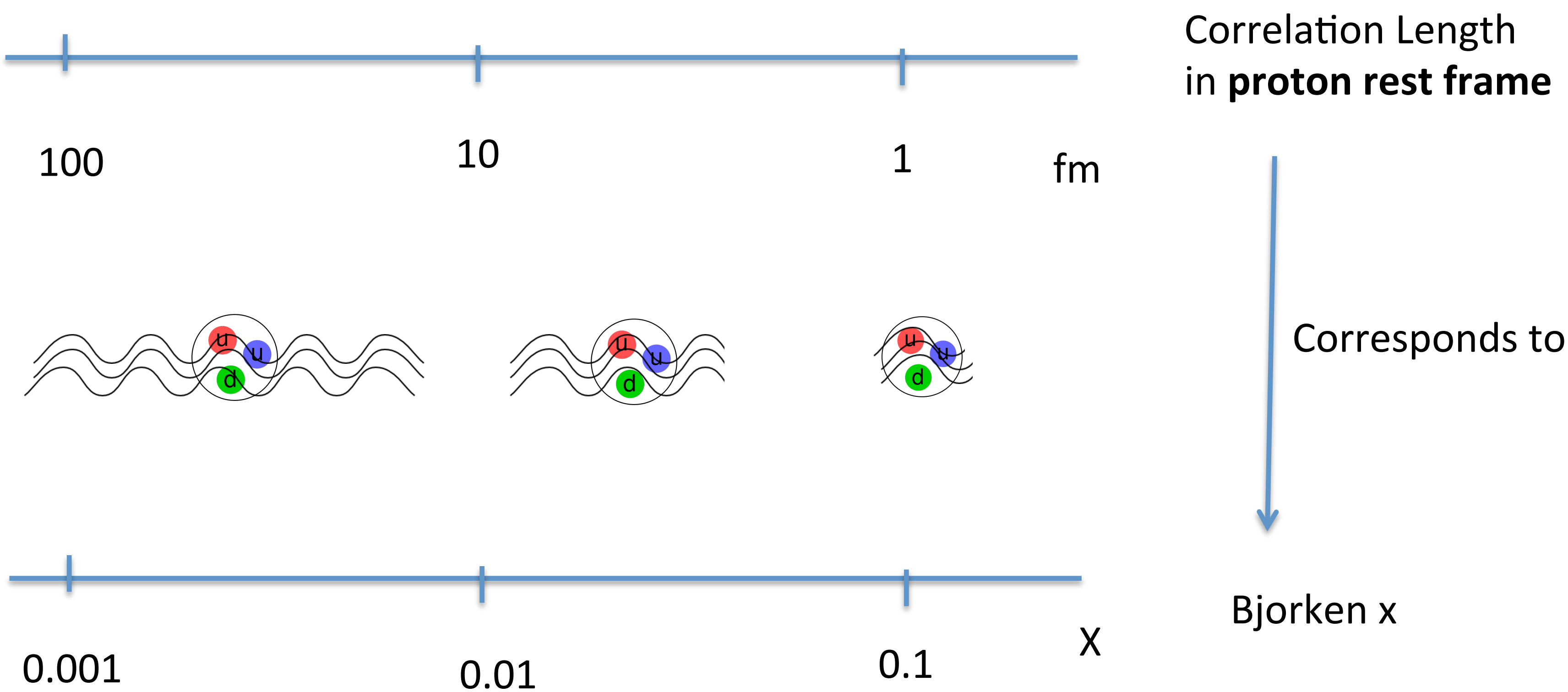
Where EIC needs to be in Q^2



- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

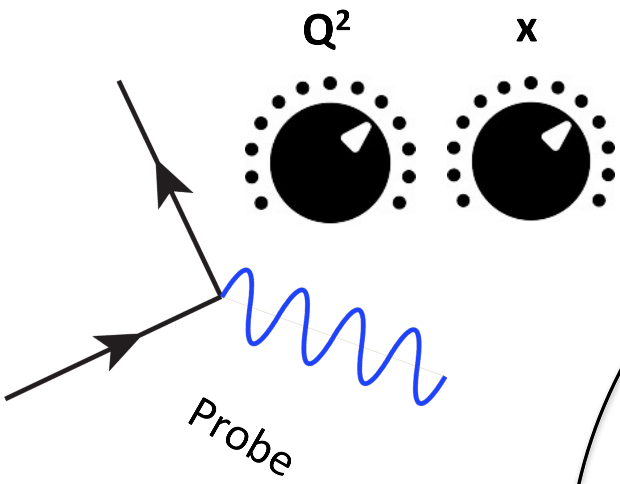
Disentangle Pert./Non-pert., Leading Twist/Higher Twist

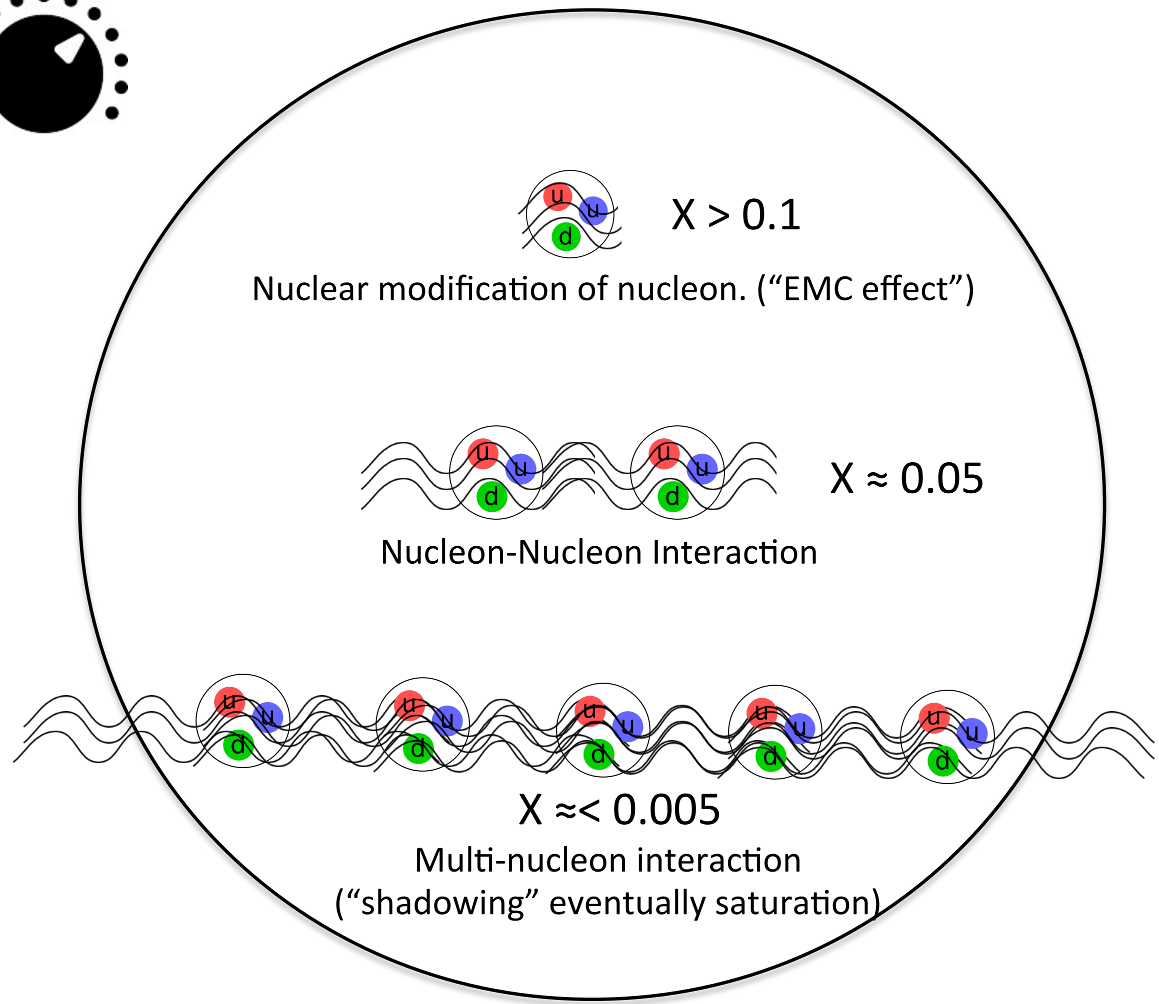
Bjorken x and length scale



In the proton rest frame, QCD field (x < 0.1) extends far beyond the proton charge radius

Understanding the Nuclei at the Next Level

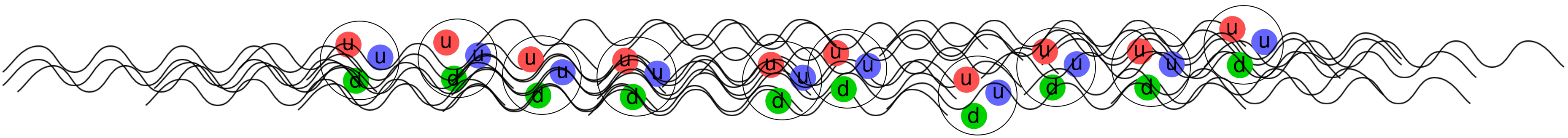




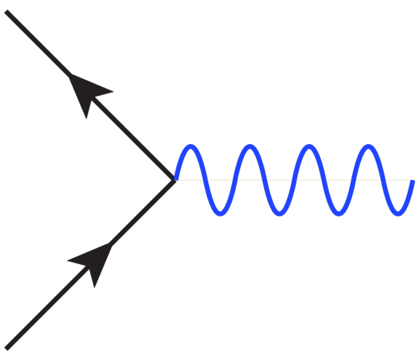
Probing the nucleon interaction in the nuclei at the parton level!!

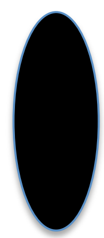
Beyond Nuclear Structure

Saturation



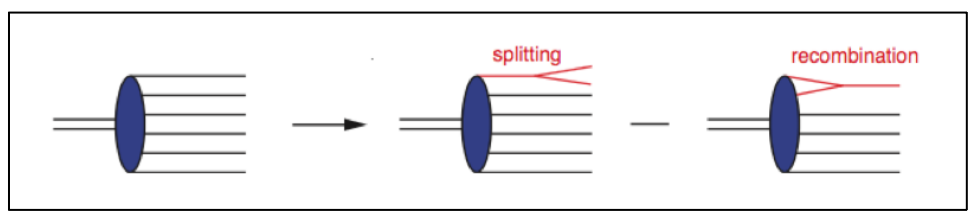
Eventually at low enough x





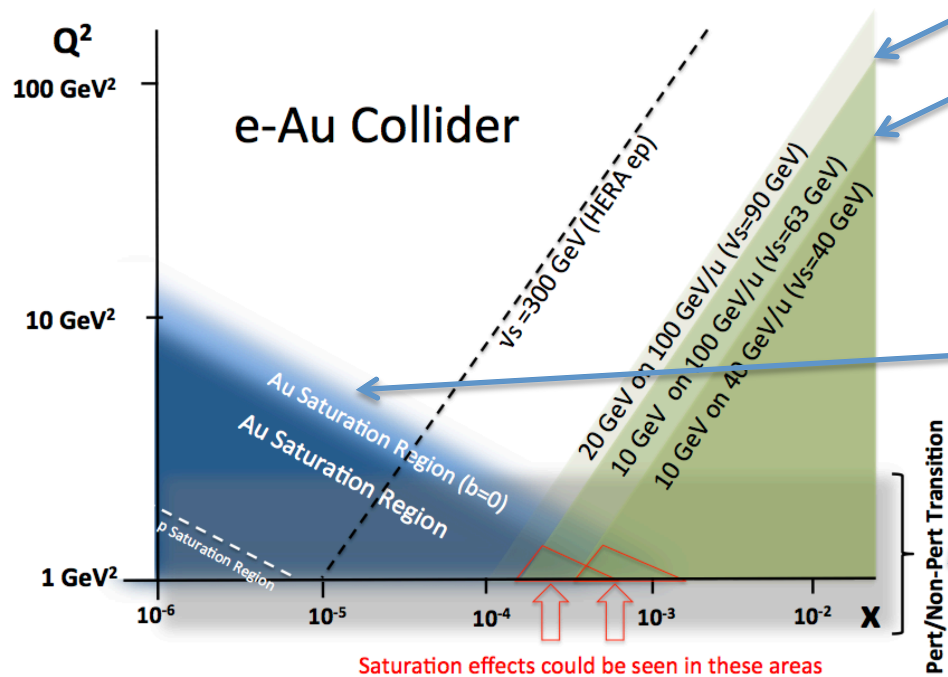
Cross-section will saturate

Equivalent to →



Can we see it at EIC?

Saturation Regime and EIC



eRHIC baseline (10x250 GeV ep)

JLEIC baseline (10x100 GeV ep)

Two competing scales

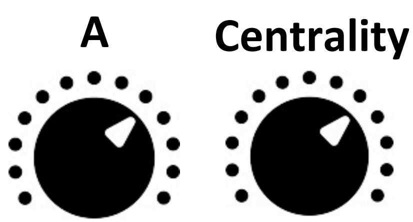
$Q_s(x)$: Saturation Scale

Q_0 : Pertutative when $Q > Q_0$

Ideally, x such that $Q_s >> Q_0$

Difficult with EIC scenarios

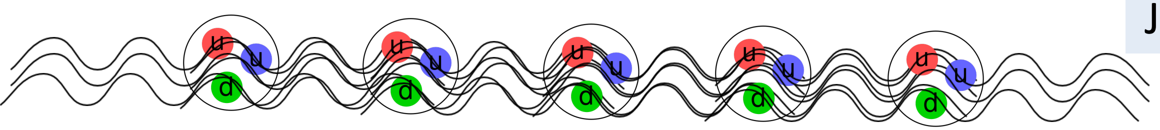
EIC has two knobs to turn



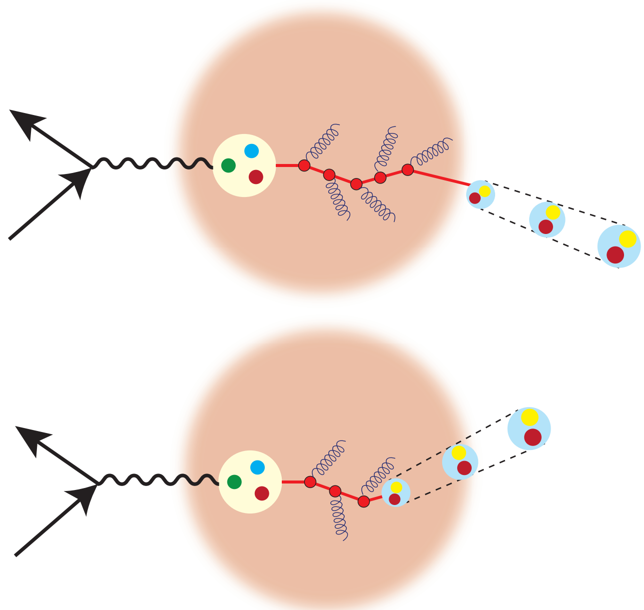
Investigate the on-set of saturation

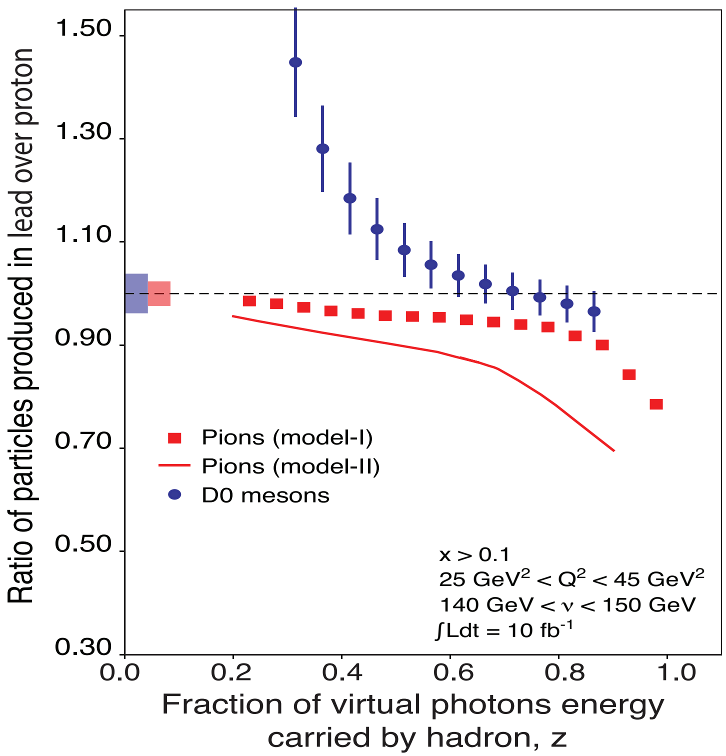
multi-nucleon coherence → saturation

JLEIC and eRHIC have similar reach



Jets, Hadronization



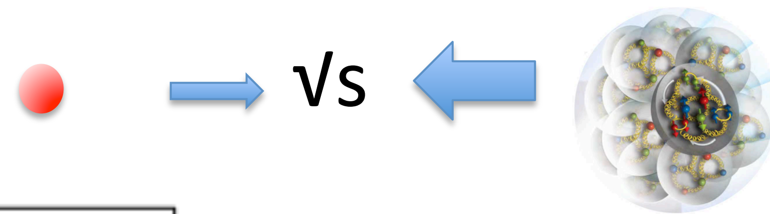


ν = E-E' = 100-200 GeV to keep jet within nucleus

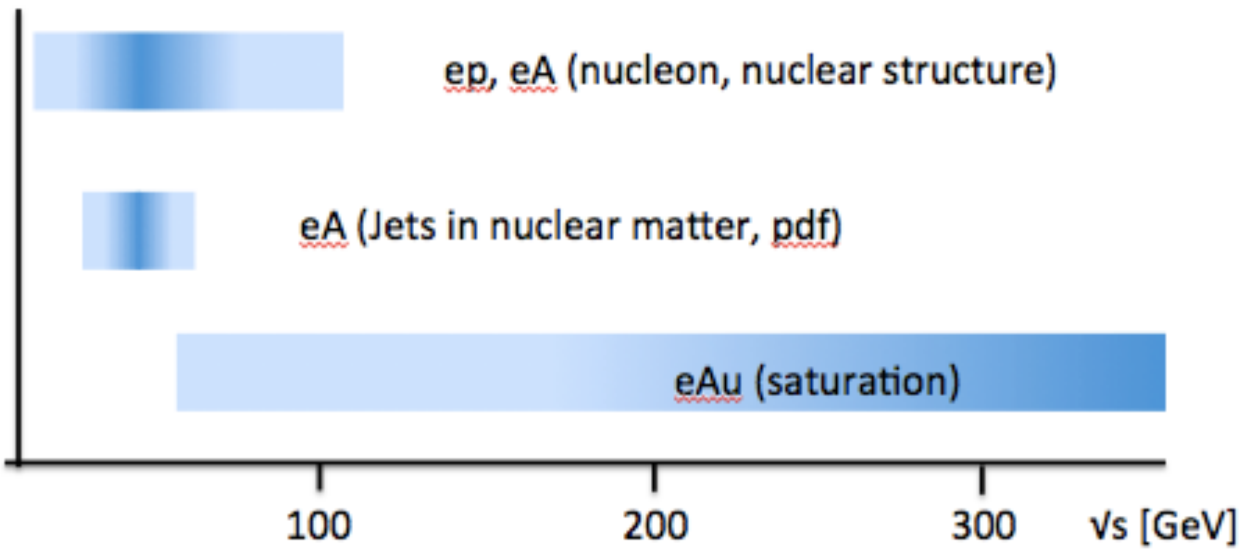
√s = 32-45 GeV for y=0.1 (keeping jet in the central region of the detector)

Designing The Right Probe: √s

What are the right parameters for the collider for the EIC science program?



√s (/u) ranges of interest



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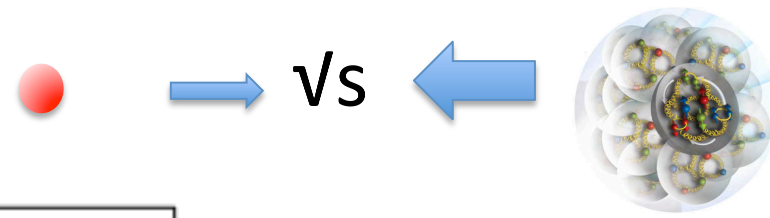

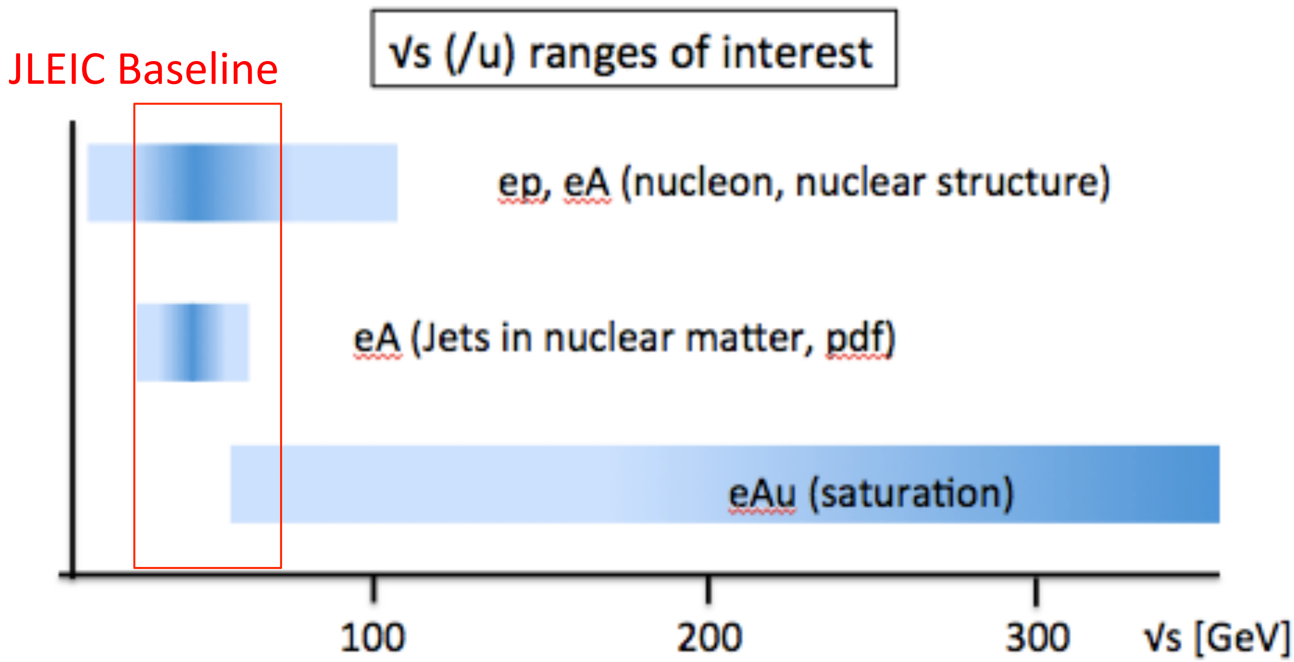

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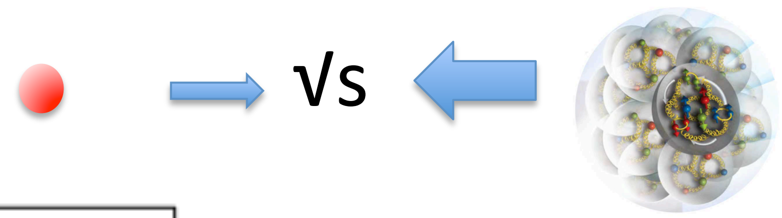
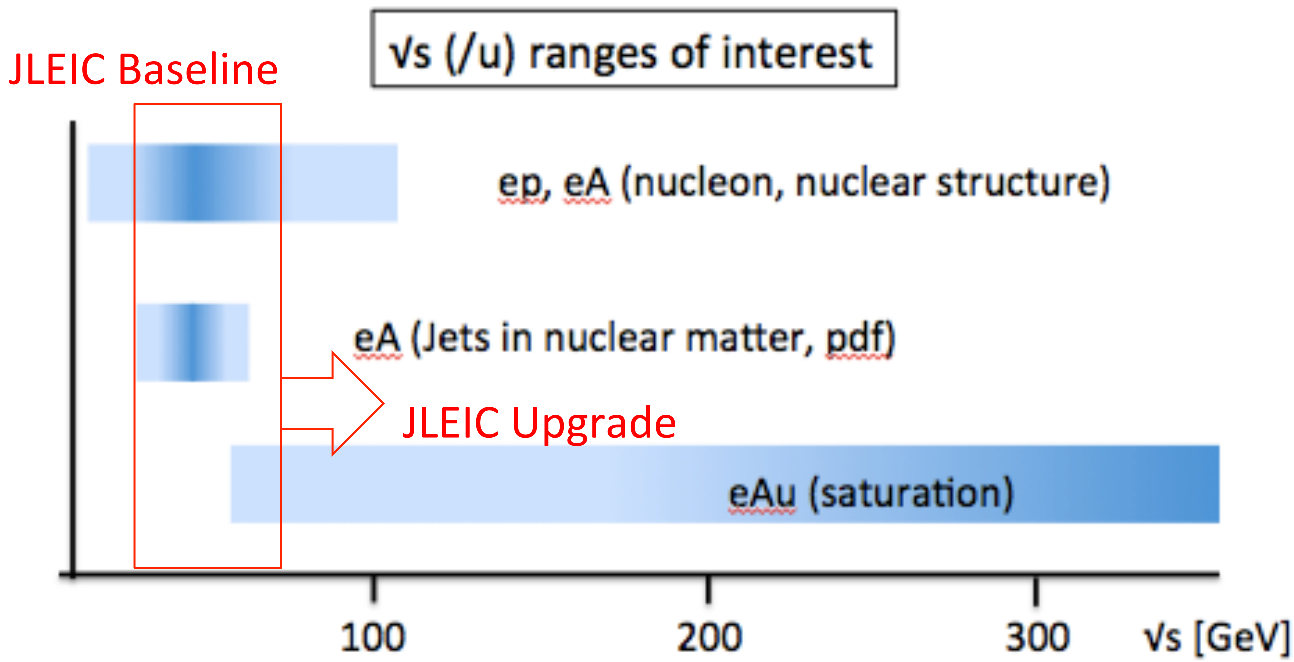
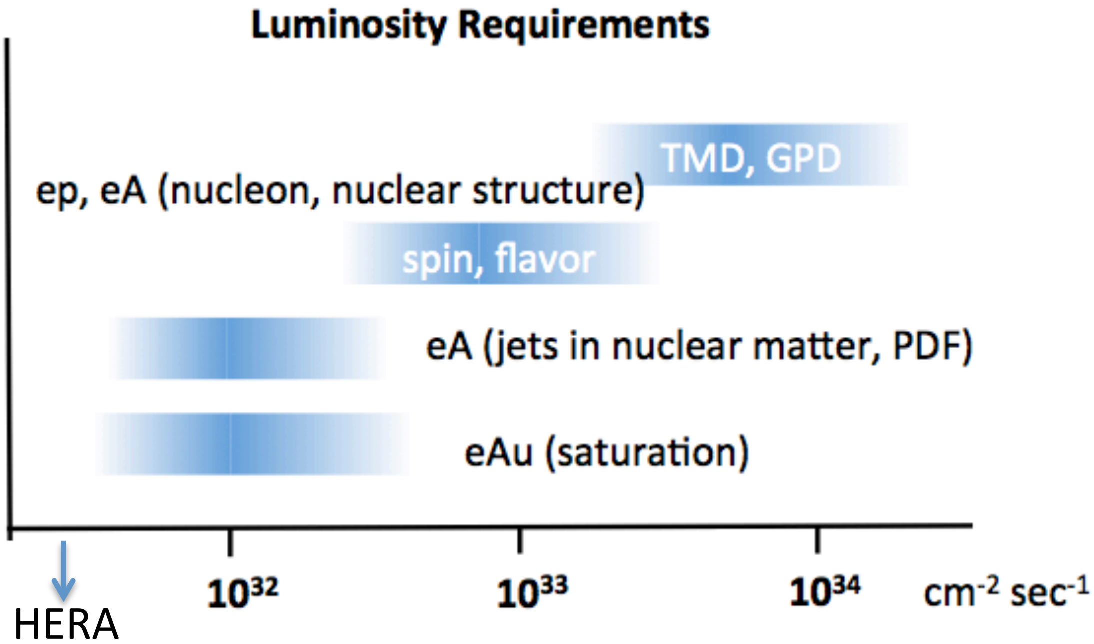




Luminosity Needed for Topics



Central mission of EIC (nuclear and nucleon structure) requires high luminosity.

Note that we cannot start the nucleon structure program without high luminosity (10^{34})

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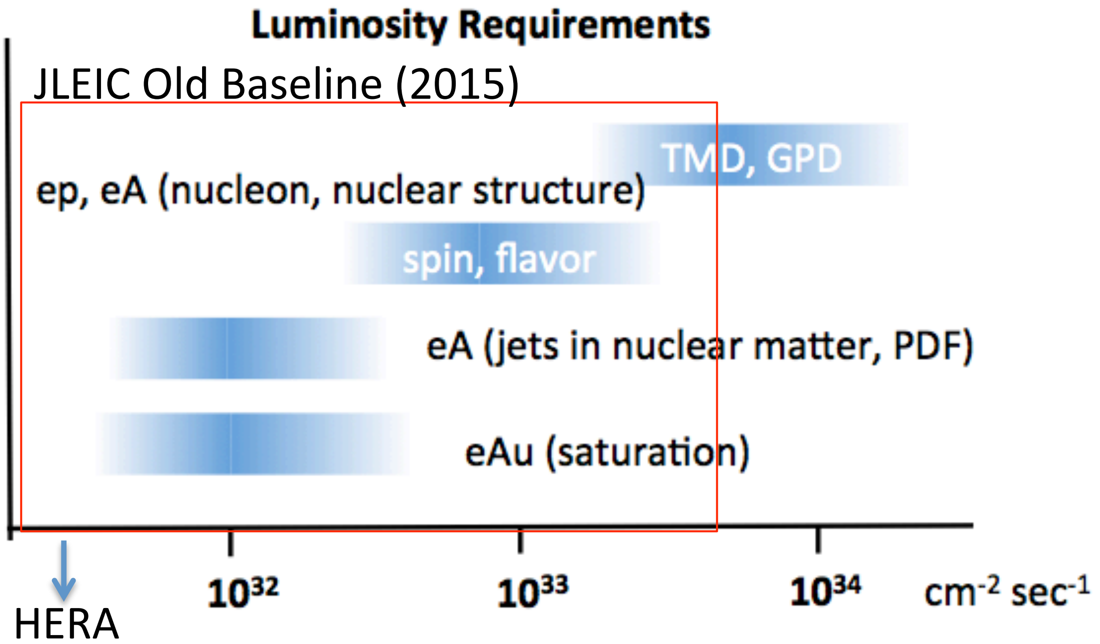

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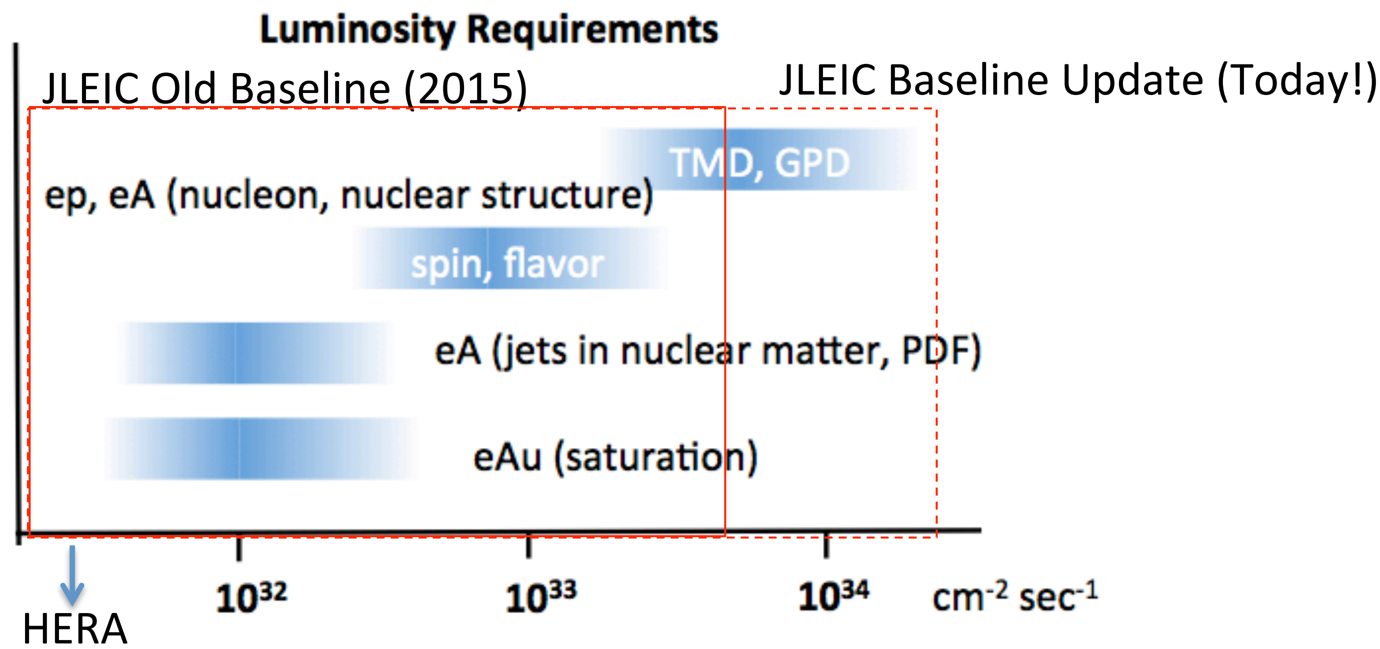

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JLEIC baseline will enable exploration of ***all*** whitepaper physics from Day 1

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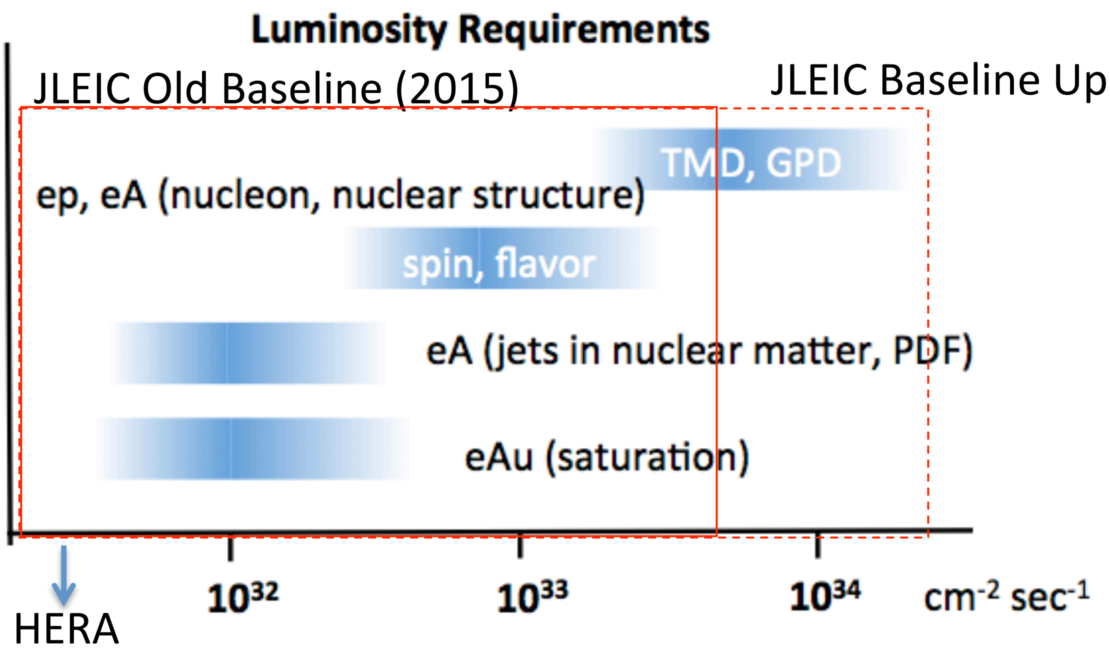

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Jefferson Lab

ACCELERATOR

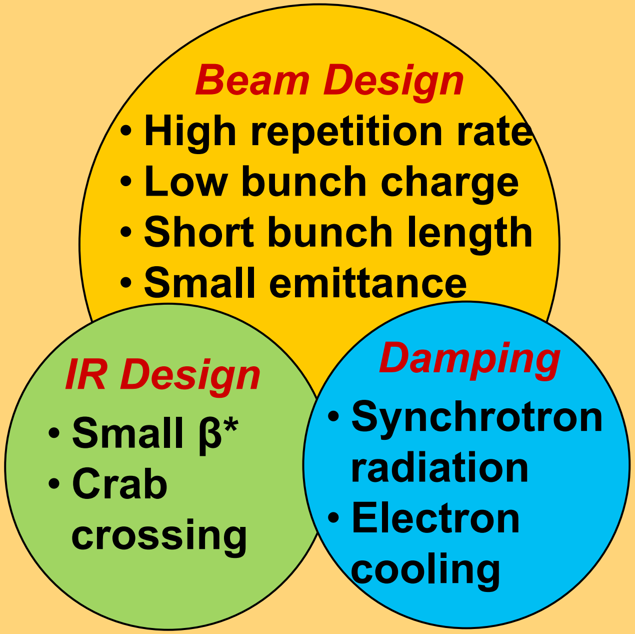
Strategy for High Luminosity and Polarization

High Luminosity

- Based on ***high bunch repetition rate CW colliding beams***

$$L = f\frac{n_1 n_2}{4\pi\sigma^*_x\sigma^*_y} \sim f\frac{n_1 n_2}{\varepsilon\beta^*_y}$$

- KEK-B reached > **2x10^{34} /cm^2/s**
- However new for proton or ion beams



High Polarization

All rings are in a figure-8 shape

➔ critical advantages for both beams

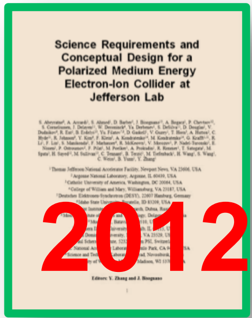
- Spin precessions in the left & right parts of the ring are ***exactly cancelled***
- Net spin precession (***spin tune***) is **zero**, thus ***energy independent***
- Spin can be ***controlled*** & ***stabilized*** by small solenoids or other compact spin rotators

Excellent Detector integration

Interaction region is designed to support

- ***Full acceptance*** detection (including forward tagging)
- Low detector ***background***

JLEIC Baseline


Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

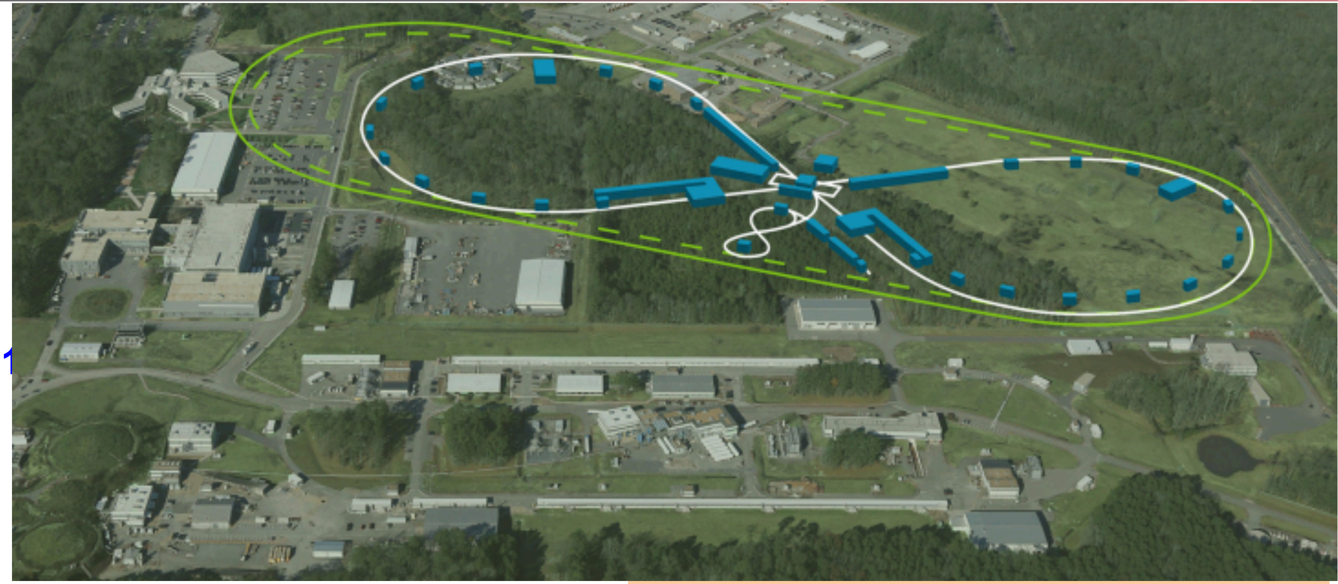
arXiv:1209.0757

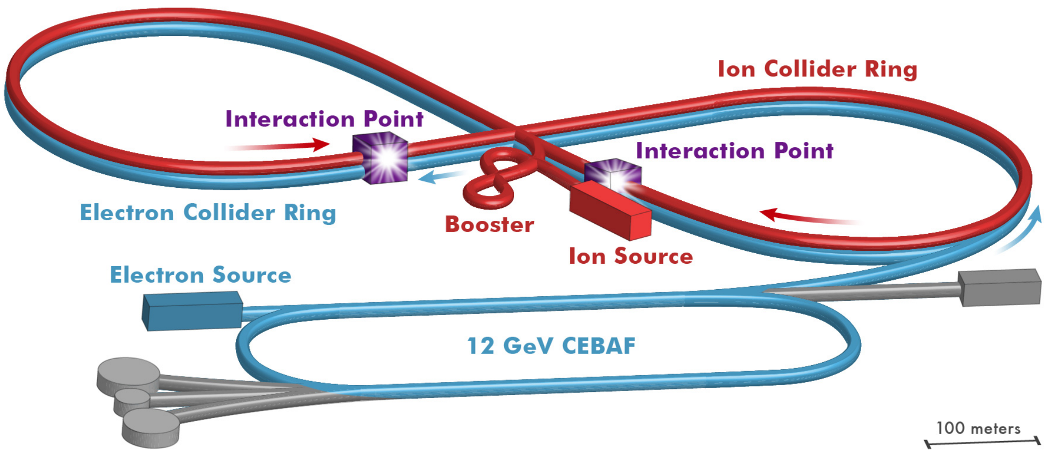

MEIC Design Summary

January 20, 2015

Author List

arXiv:1504.07961

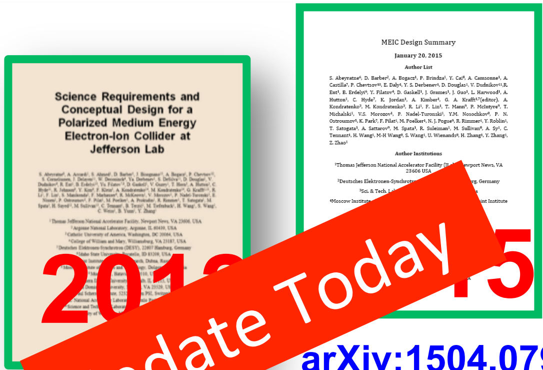




Baseline [upgrade] energy range:
e-: 3-10 [12] GeV
p : 20-100 [200] GeV

Cooling strategy:
- **DC cooler** in booster
- **Bunched beam cooler** in Ion collider ring

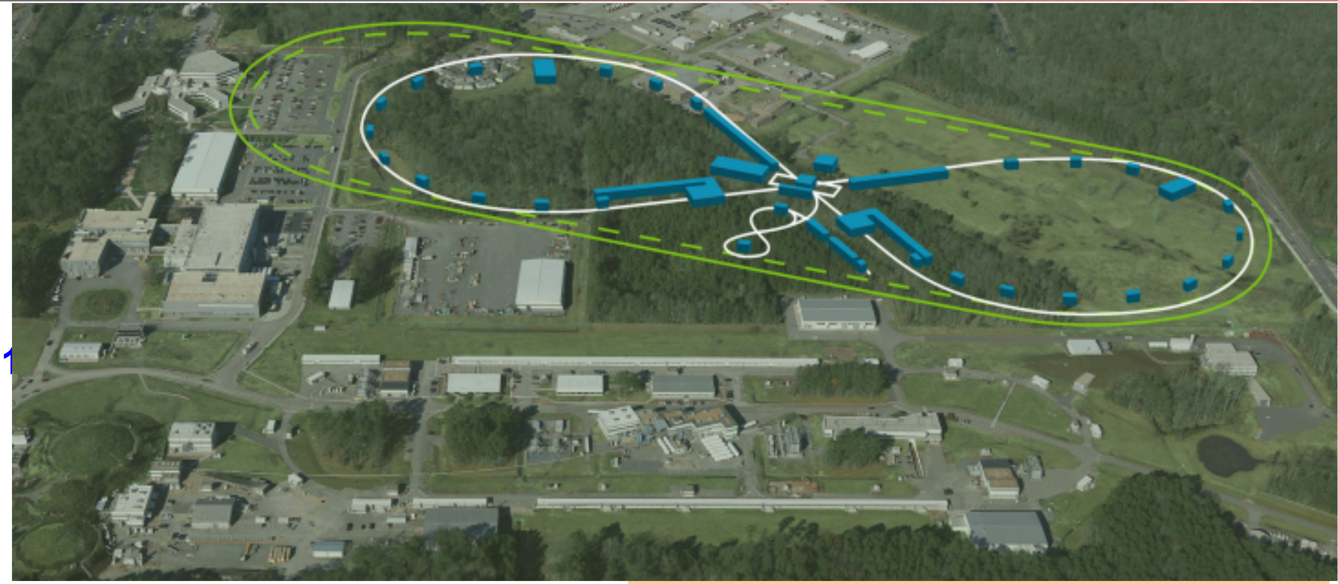
JLEIC Baseline

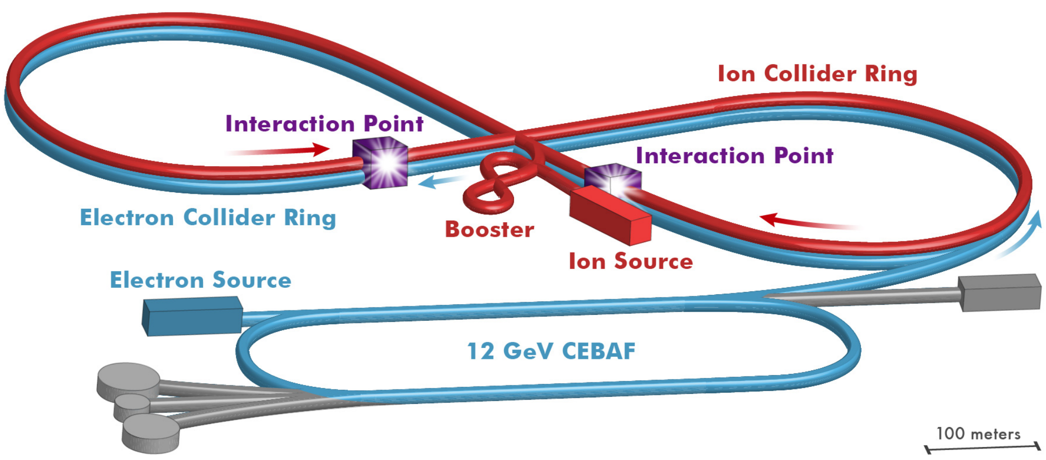


Update Today

arXiv:1504.07961

a ...209.0757





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EIC design and R&D focus areas

Bunched beam electron cooling

- ERL Cooler design (JLAB)
- Magnetized source for e-cooler (JLAB LDRD, Cornell SBIR)
- Bunched beam cooling experiment (JLAB, IMP)
- Fast kicker for recirculator cooler (JLAB)

Magnets for the ion booster and collider

- Super-ferric magnet R&D for 3T , prototype (Texas A&M, JLAB)
- Super-conducting magnets design for 3T (LBL)
- IR magnets design (Texas A&M, LBL)

SRF cavities and crab cavities

- 952 MHz crab cavity design, integration, prototype (ODU-JLAB)
- 952 MHz SRF cavities for cooler and ion collider: (JLAB)

Ion injector

- SRF linac design, stripping, simulations (ANL, JLAB)
- Evaluation warm vs. cold linac (MSU)

Interaction Regions and beam dynamics

- IR design, detector interface, backgrounds, collimation (SLAC, JLAB)
- Non-linear dynamics, corrections, DA (SLAC, JLAB)
- **Beam physics and modeling** (JLAB, ODU, LBL, ANL, SLAC)

1st beam tests – preliminary results

- A collaboration of JLAB and Institute of Modern Physics (IMP), China
- The 1st experiment was carried out on **May 17-22**, 2016, at Lanzhou, China

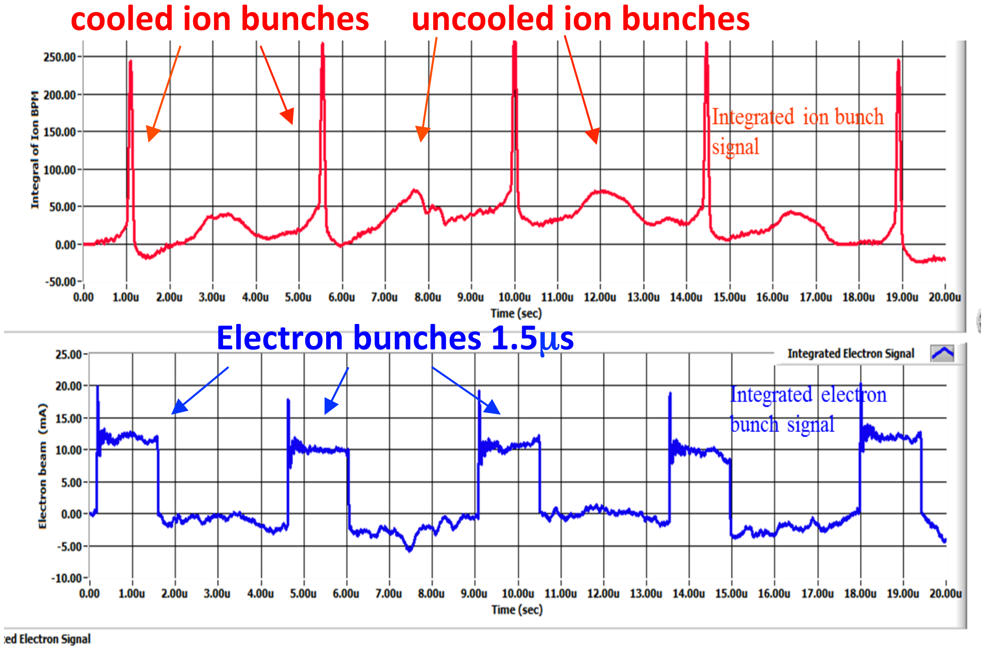
- A 7MeV/u $^{12}C^{6+}$ **ion beam** stored in the IMP CSRm ring, either coasting or captured by 450kHz RF system (two long bunches)

- **Cooling of both coasting and bunched ion by a pulsed electron beam are observed: first successful step of experimental demonstration of bunched beam cooling**

- **Data analysis** both at IMP and JLAB is in progress

- Initial 1D **modeling** with RF capture and bunching shows the ion cooling and synchrotron sideband effects, agree with experimental observations

Experiment data observation on BPMs



JLEIC (2016) with bunched beam cooling at collision

Parameters		Single-turn ERL Cooler PEP-II e-ring		Multi-turn ERL Cooler New e-ring	
		p	e	p	e
Beam energy	GeV	100	5	100	5
Collision frequency	MHz	476		476	
Particles per bunch	10^{10}	0.66	3.9	0.98	3.7
Beam current	A	0.5	3	0.75	2.82
Polarization		>70%	>70%	>70%	>70%
Bunch length, rms	cm	1	1.2	1.2	1.2
Norm. emittance, x/y	µm	1/0.5	144/72	0.5/0.1	70/14
x/y β*	cm	4/2	2.6/1.3	6/1.2	4/0.8
Vert. beam-beam param.		0.006	0.014	0.015	0.053
Laslett tune shift		0.01	Small	0.048	Small
Detector space, up/down	m	3.6/7	2.4/1.6	3.6/7	2.4/1.6
Hourglass (HG) reduction		0.88		0.80	
Lumi./IP, w/HG, **10^{33}**	$cm^{-2}s^{-1}$	4.6		19.5	

2015 MEIC Design Report

2016 JLEIC Baseline Update

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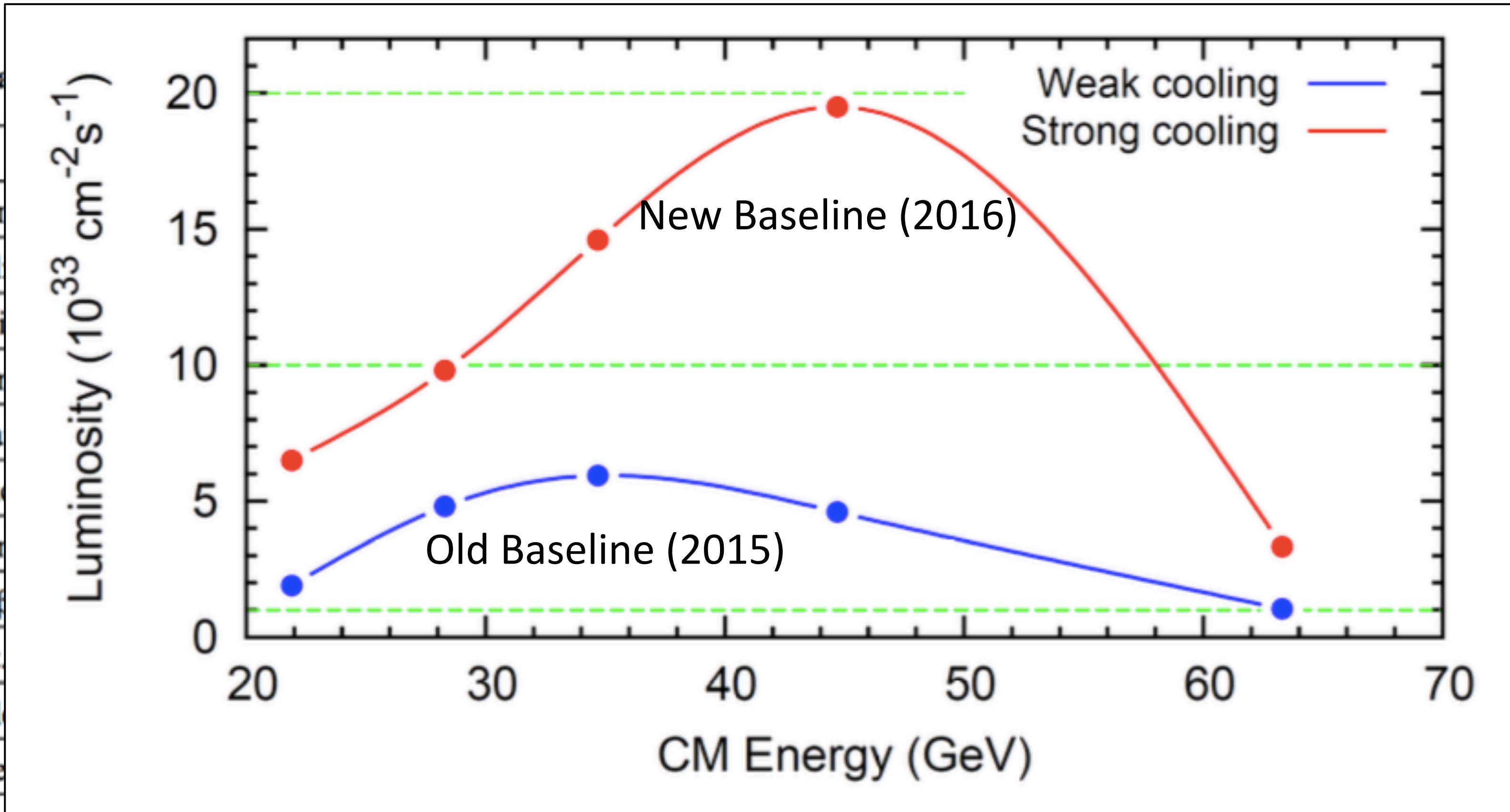

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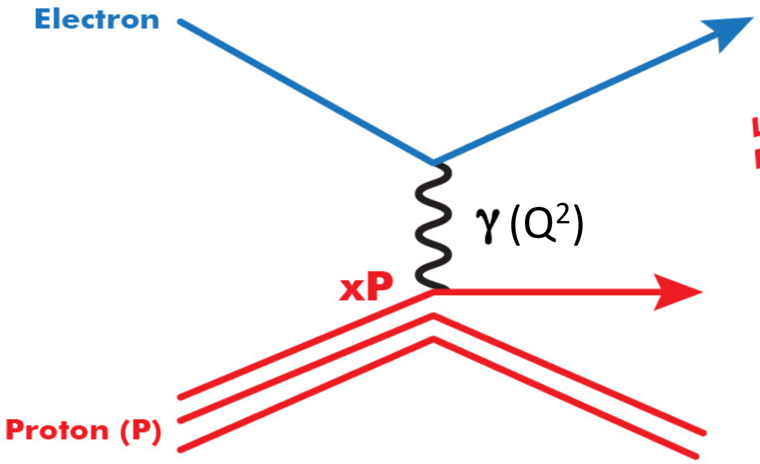
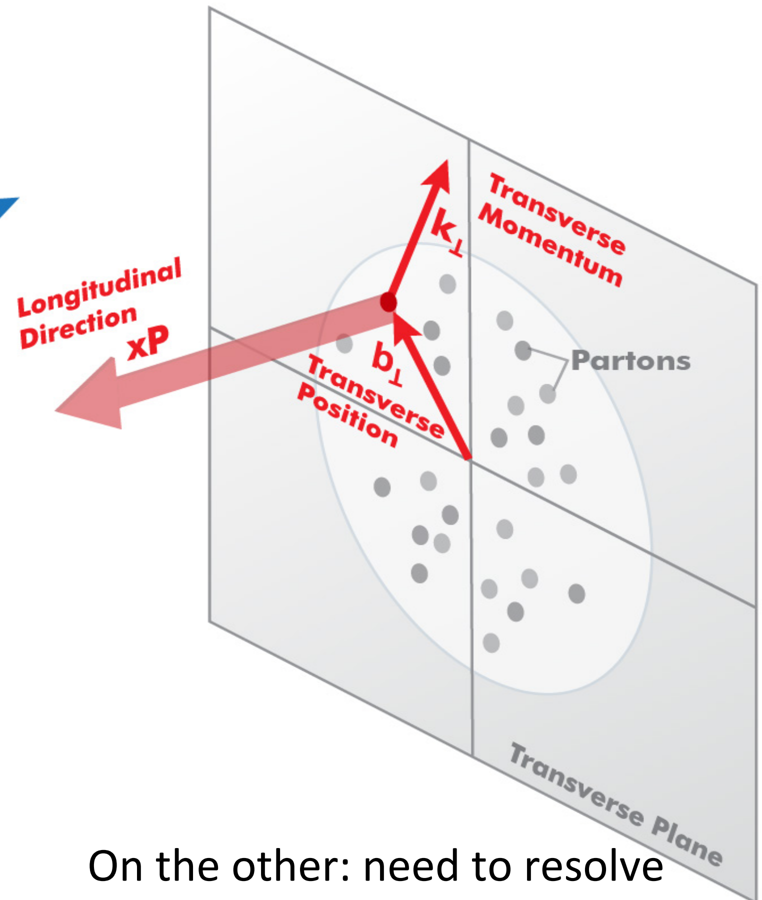
IR AND DETECTOR

Experimental Challenge of the EIC

$s = xyQ^2$, $s = 4E_eE_p$



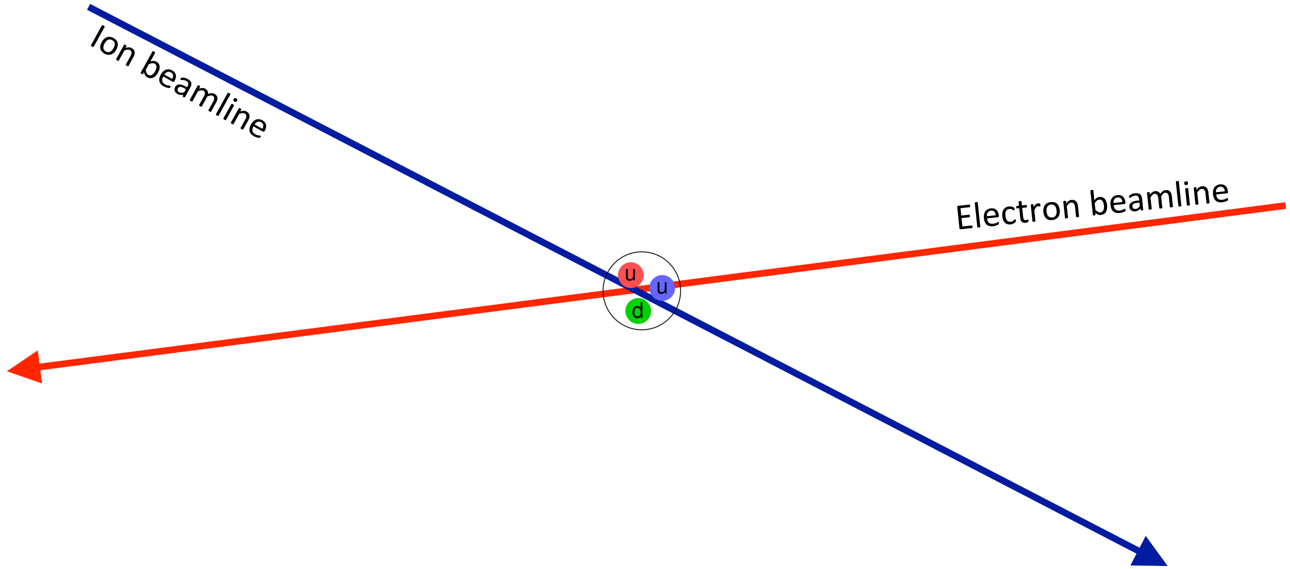


On one hand: need high beam energies to resolve partons in nucleons.
Q^2 needs to be up to ~1000 GeV^2

On the other: need to resolve quantities (k_t, b_t) of order a few hundred MeV in the proton. Limits proton beam energy. High Lumi needed.

Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

EIC Final State Particles



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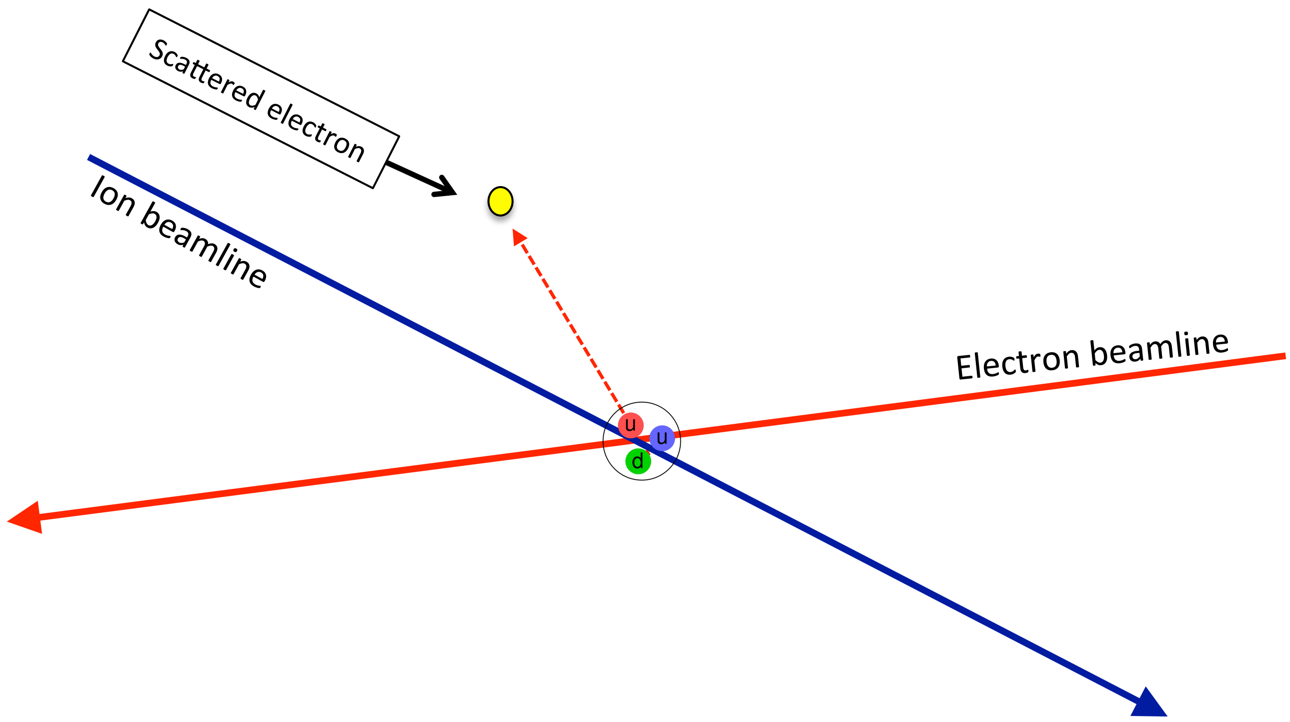

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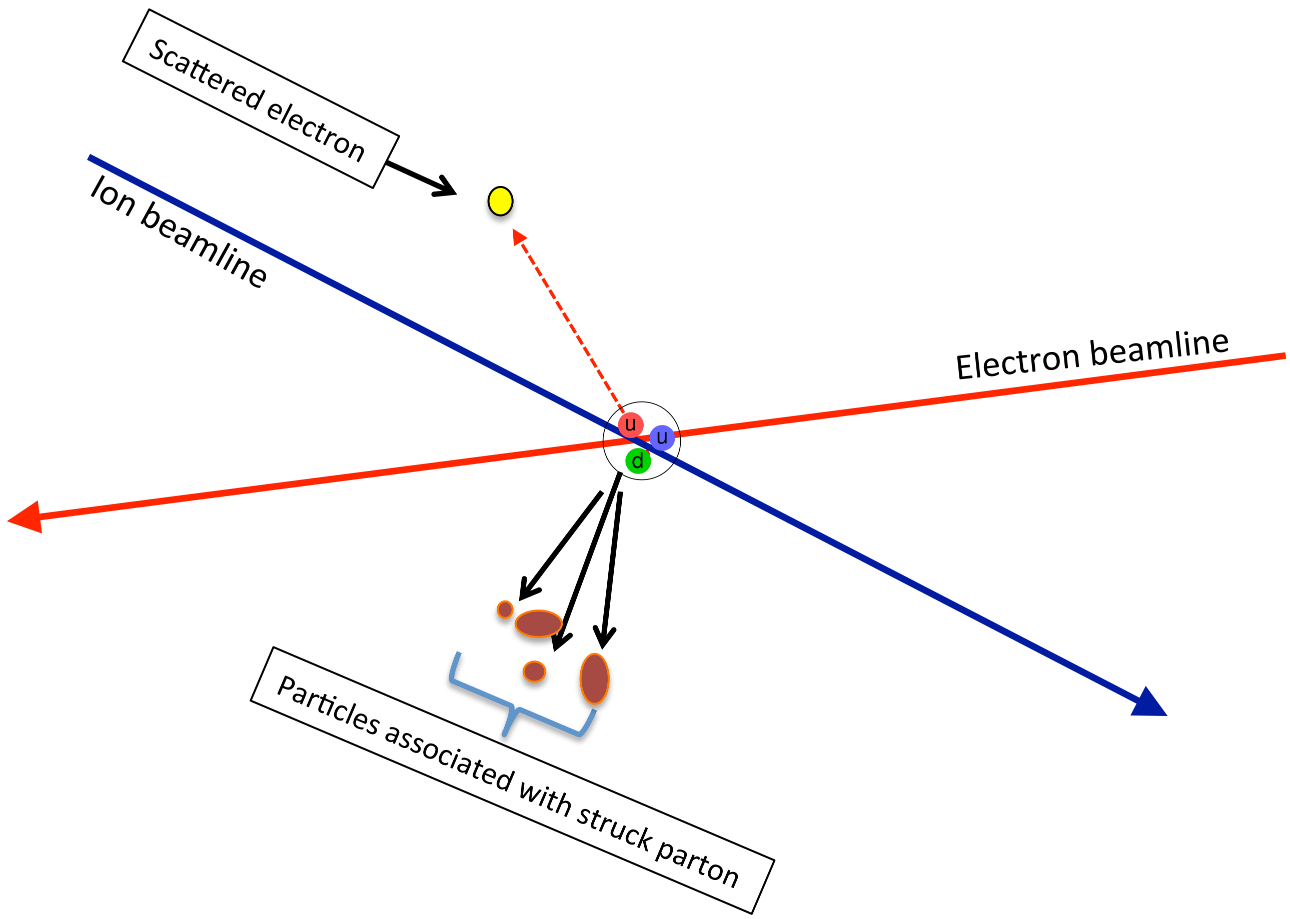

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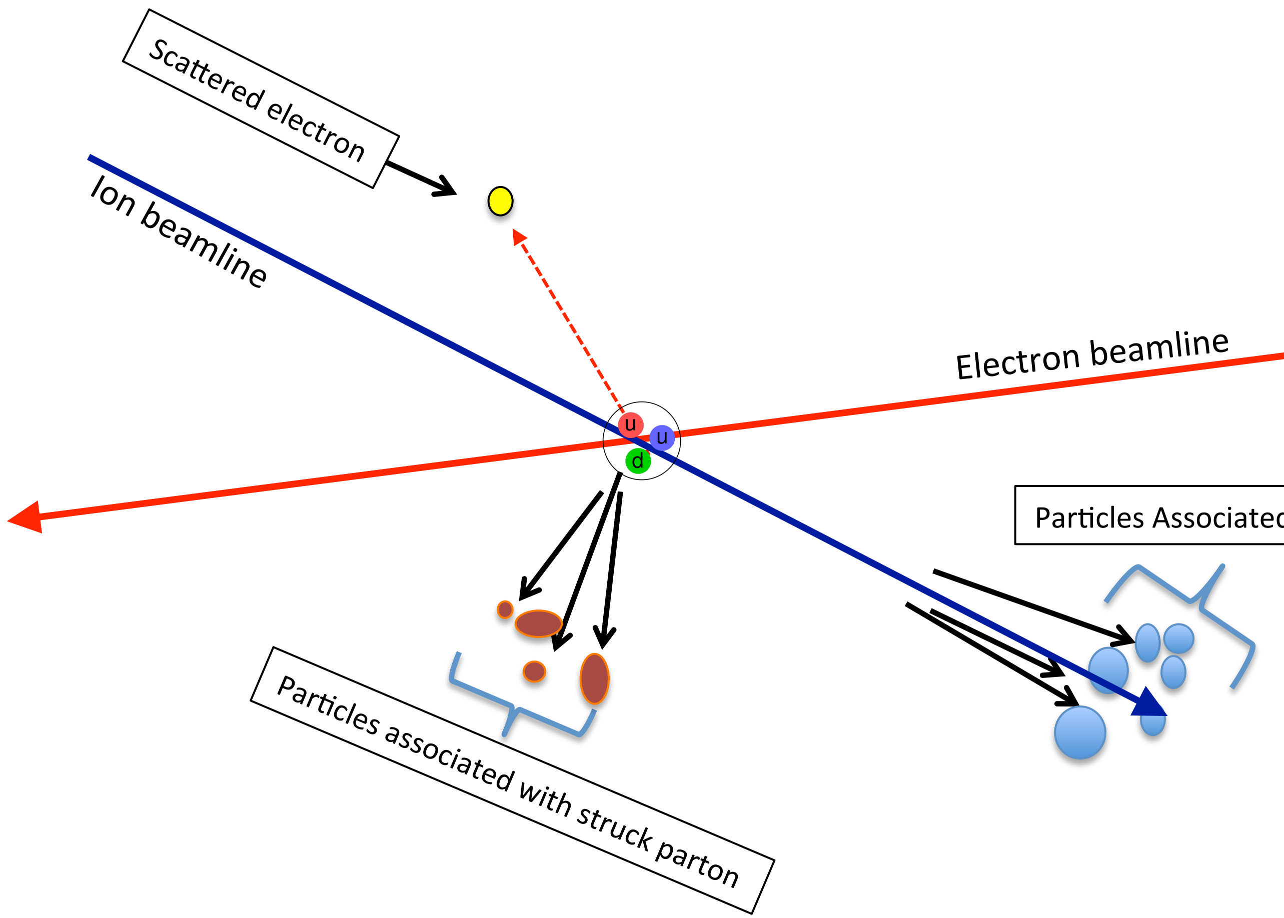

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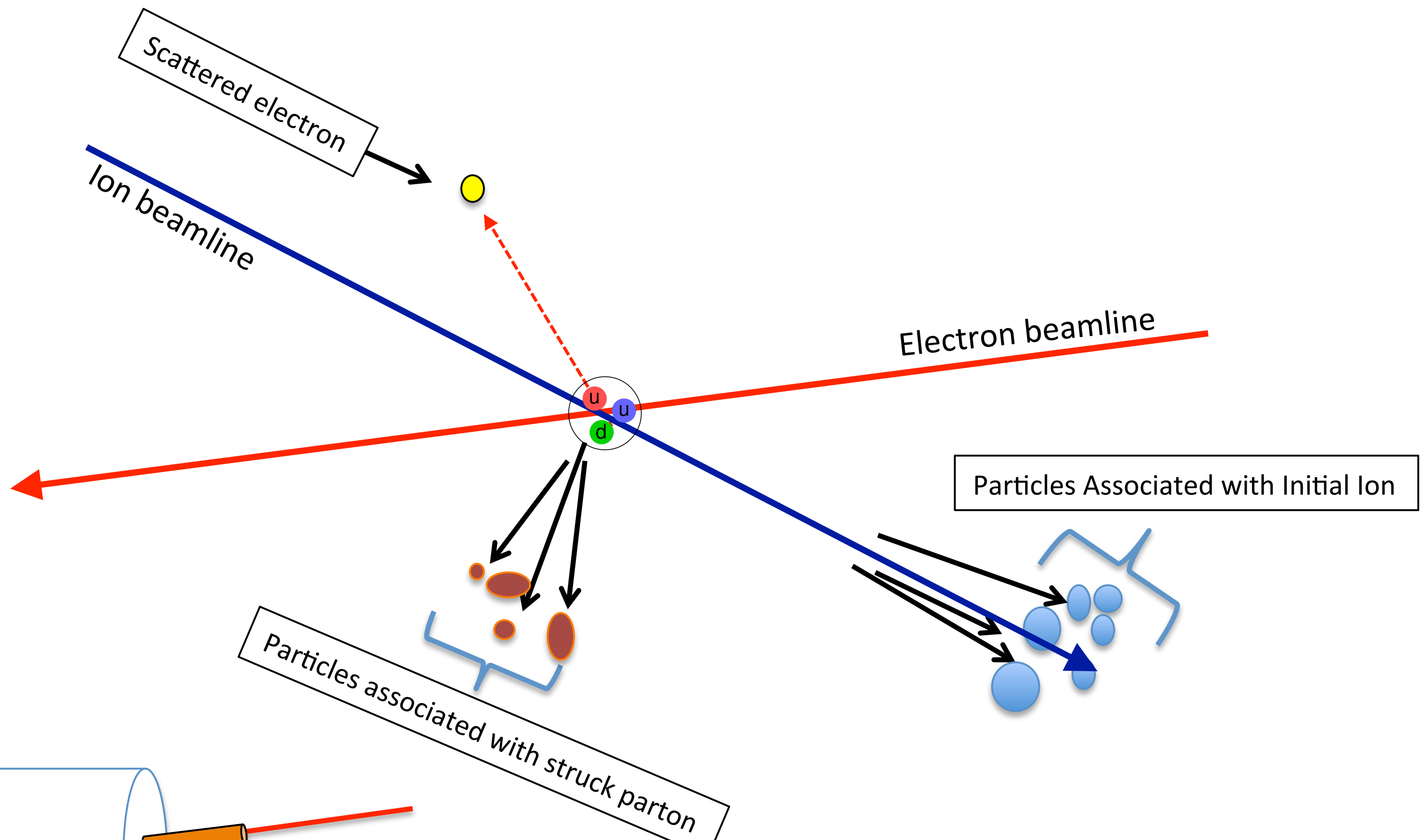
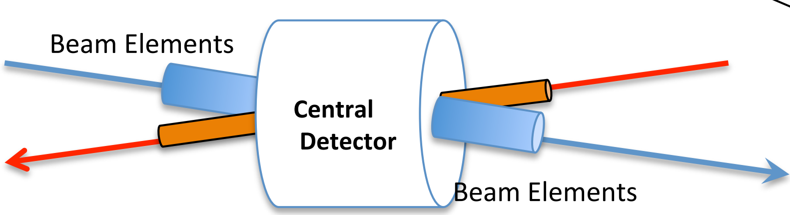
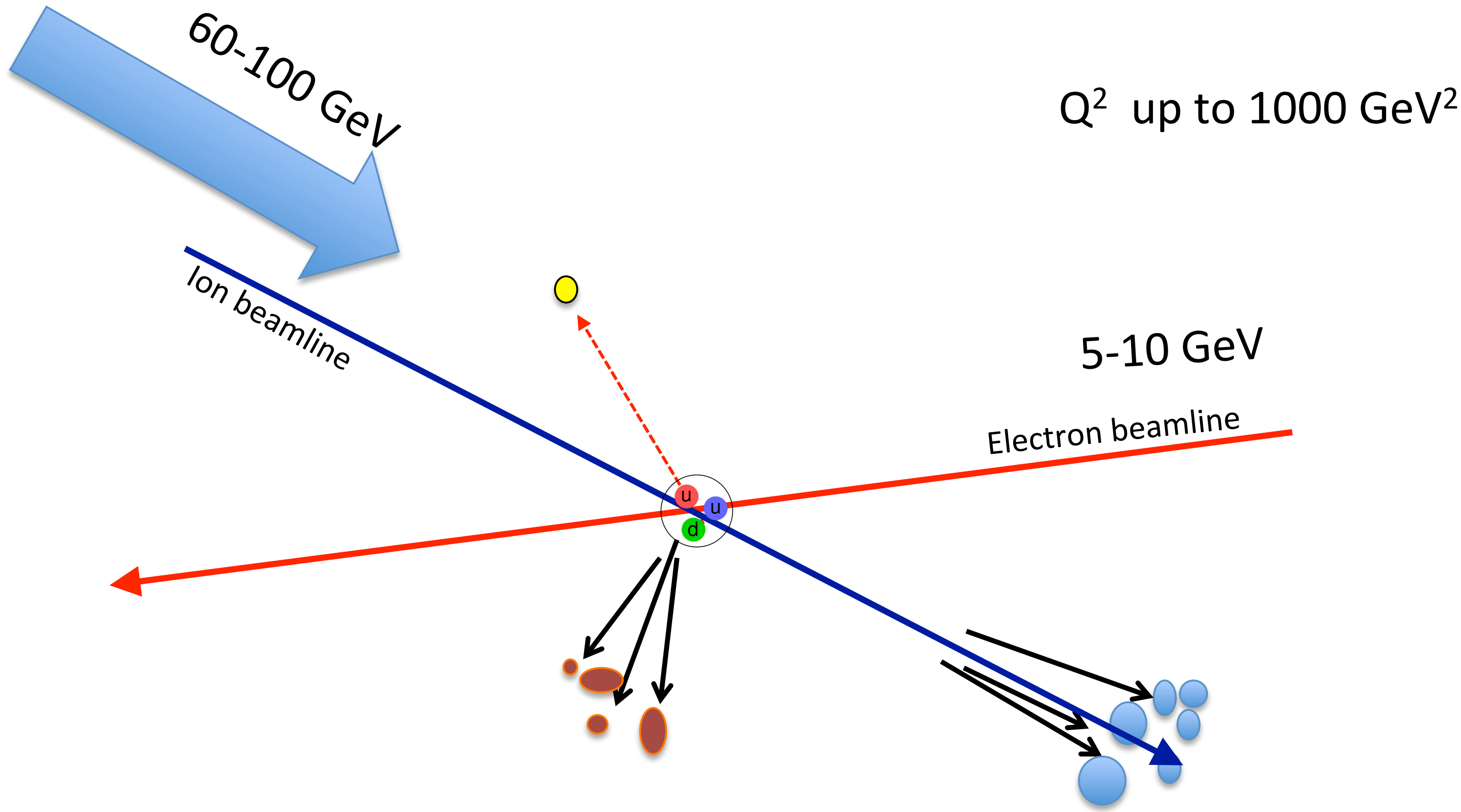




Beam elements limit forward acceptance
Central Solenoid not effective for forward

Measuring k_t and b_t



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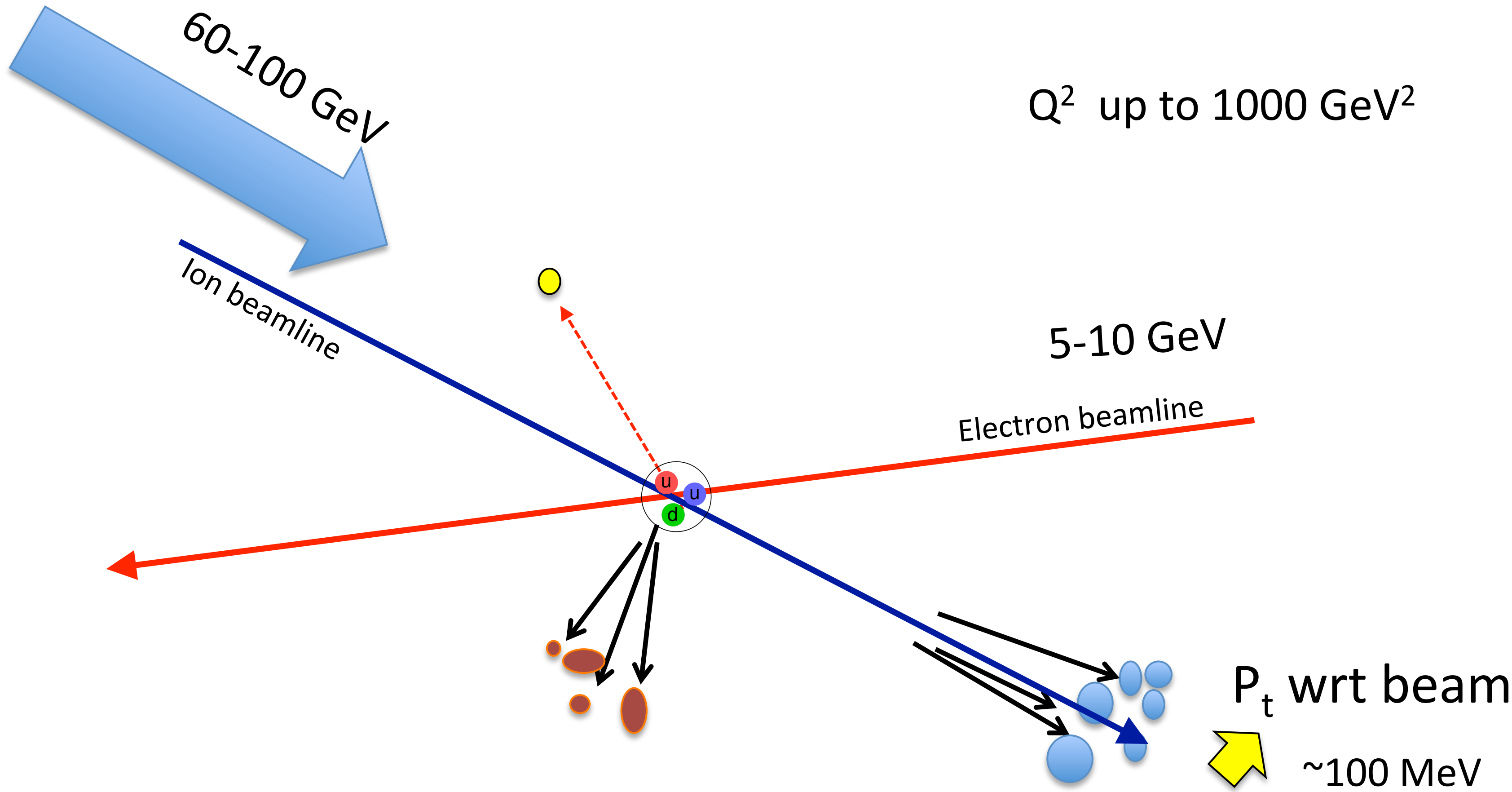

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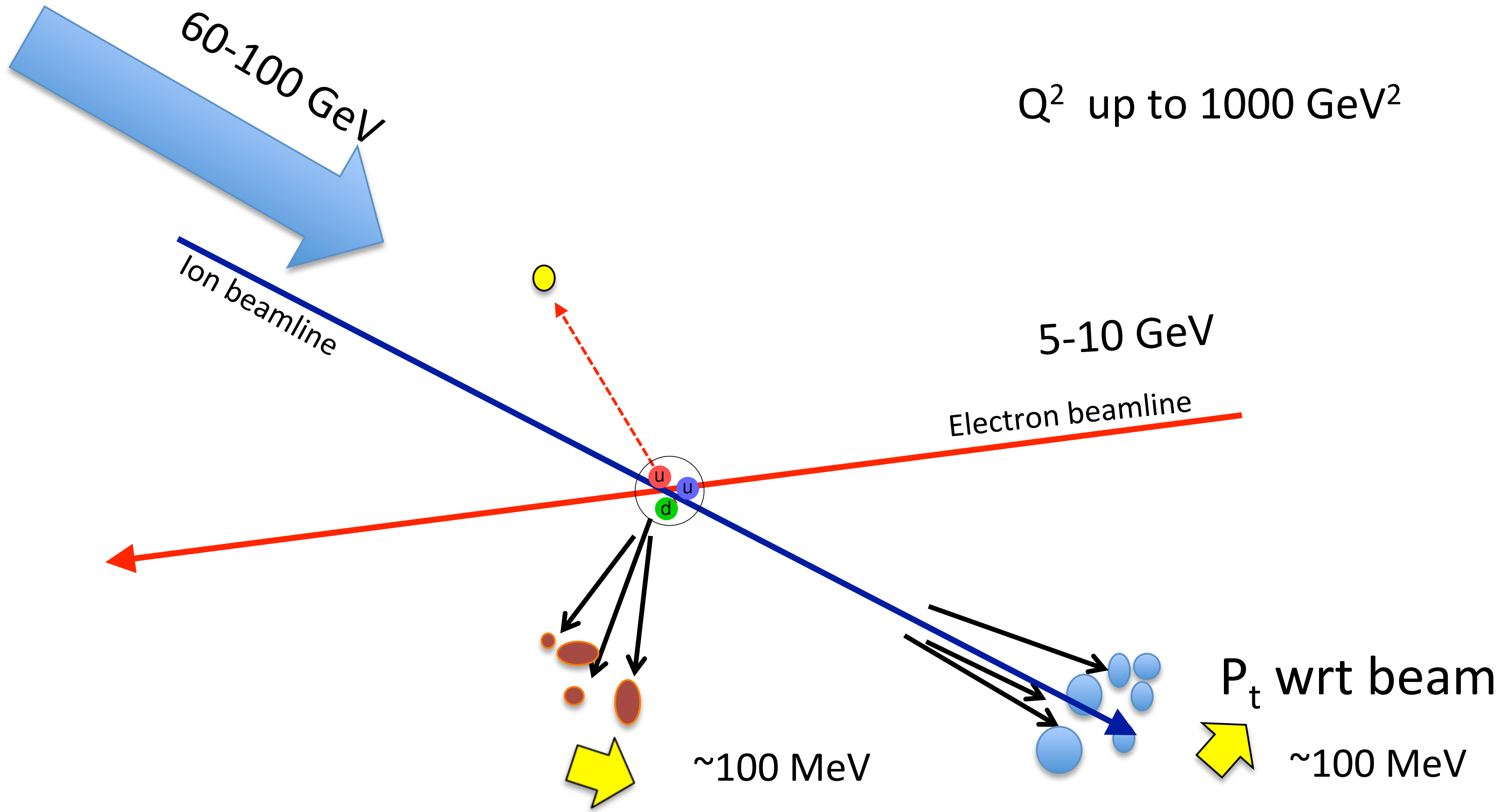
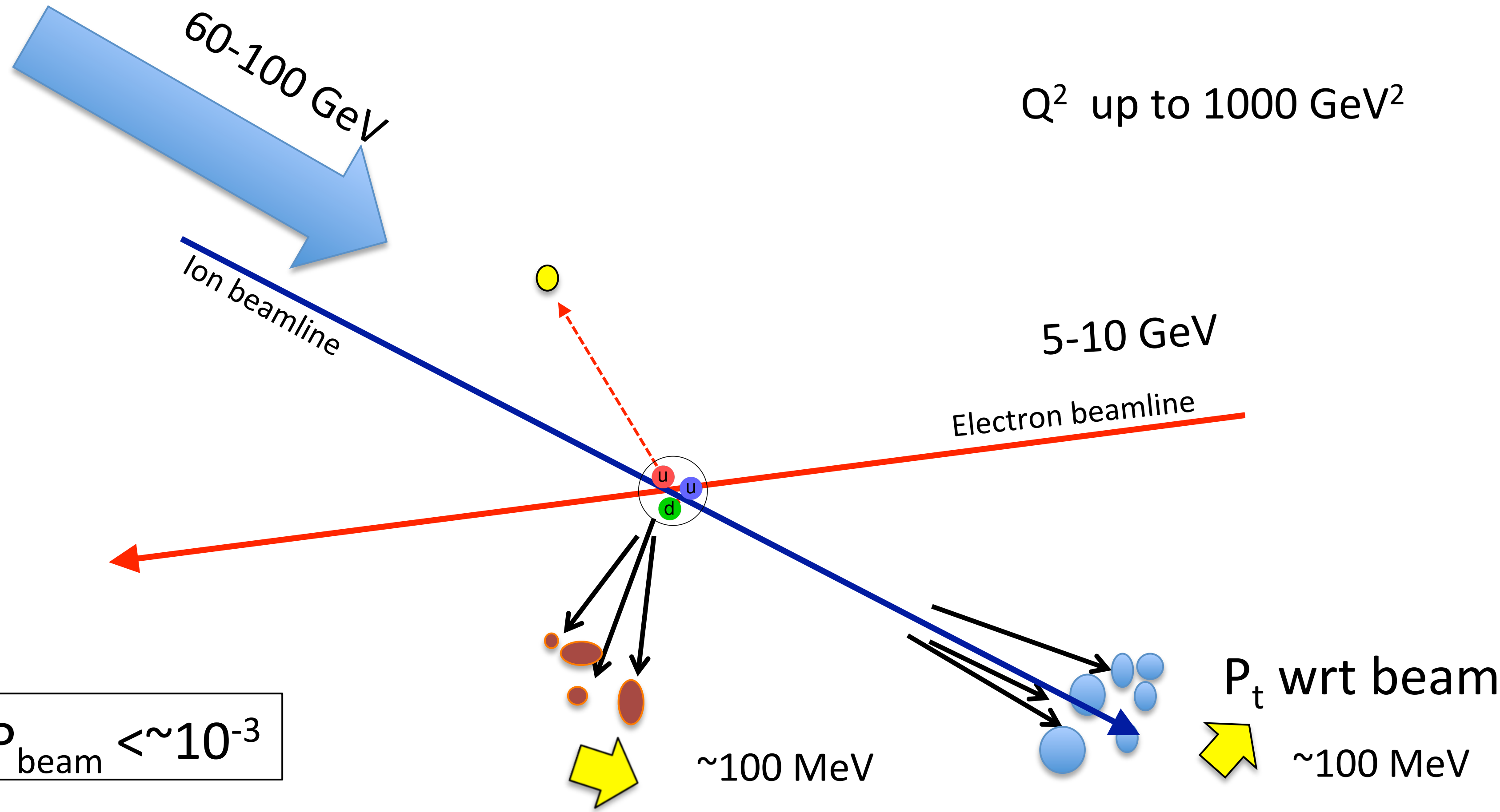


P_t wrt scattering plane.
+ particle ID

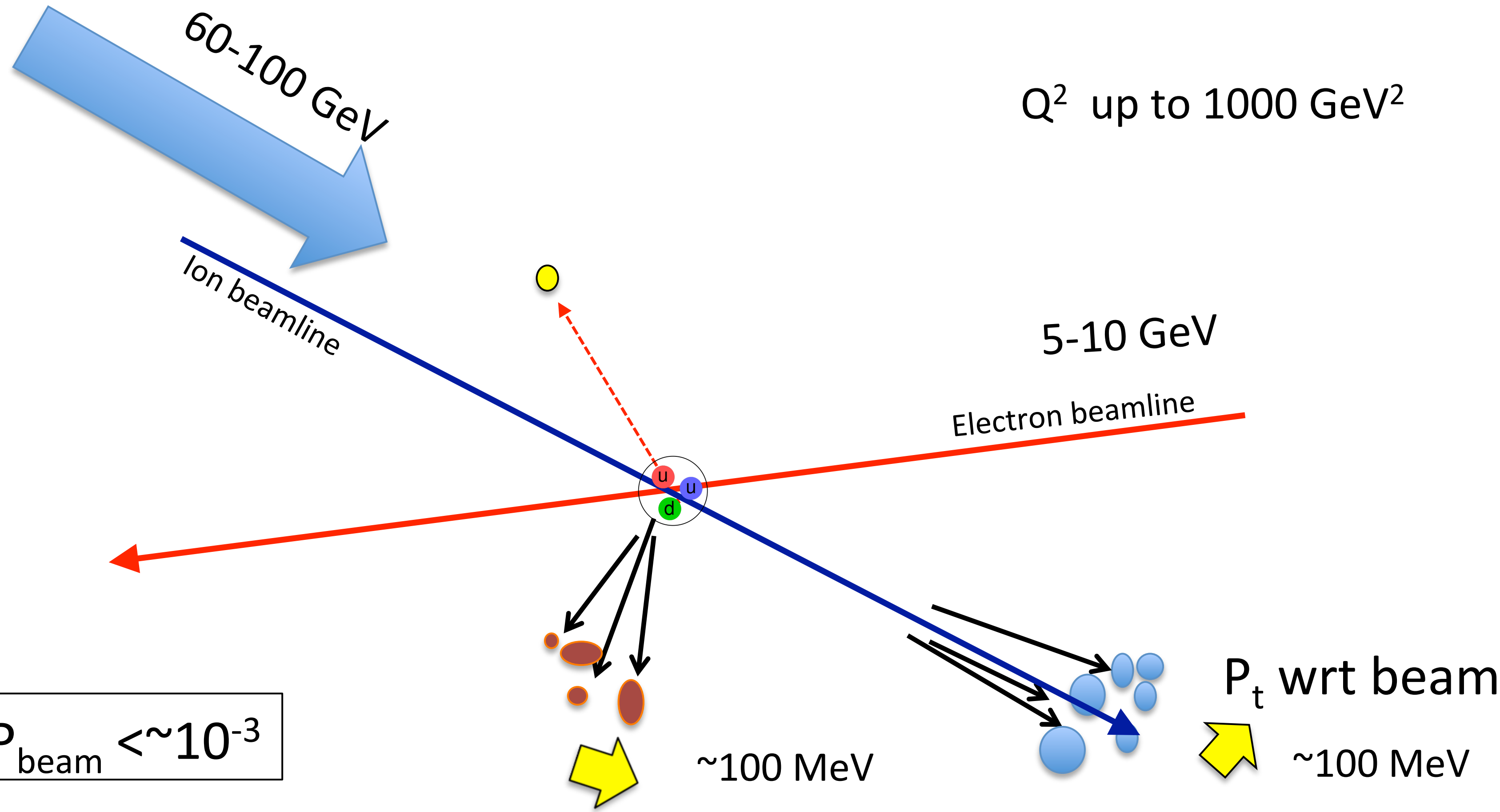
Measuring k_t and b_t



P_t/P_{beam} <~10^{-3}

P_t wrt scattering plane.
+ particle ID

Measuring k_t and b_t

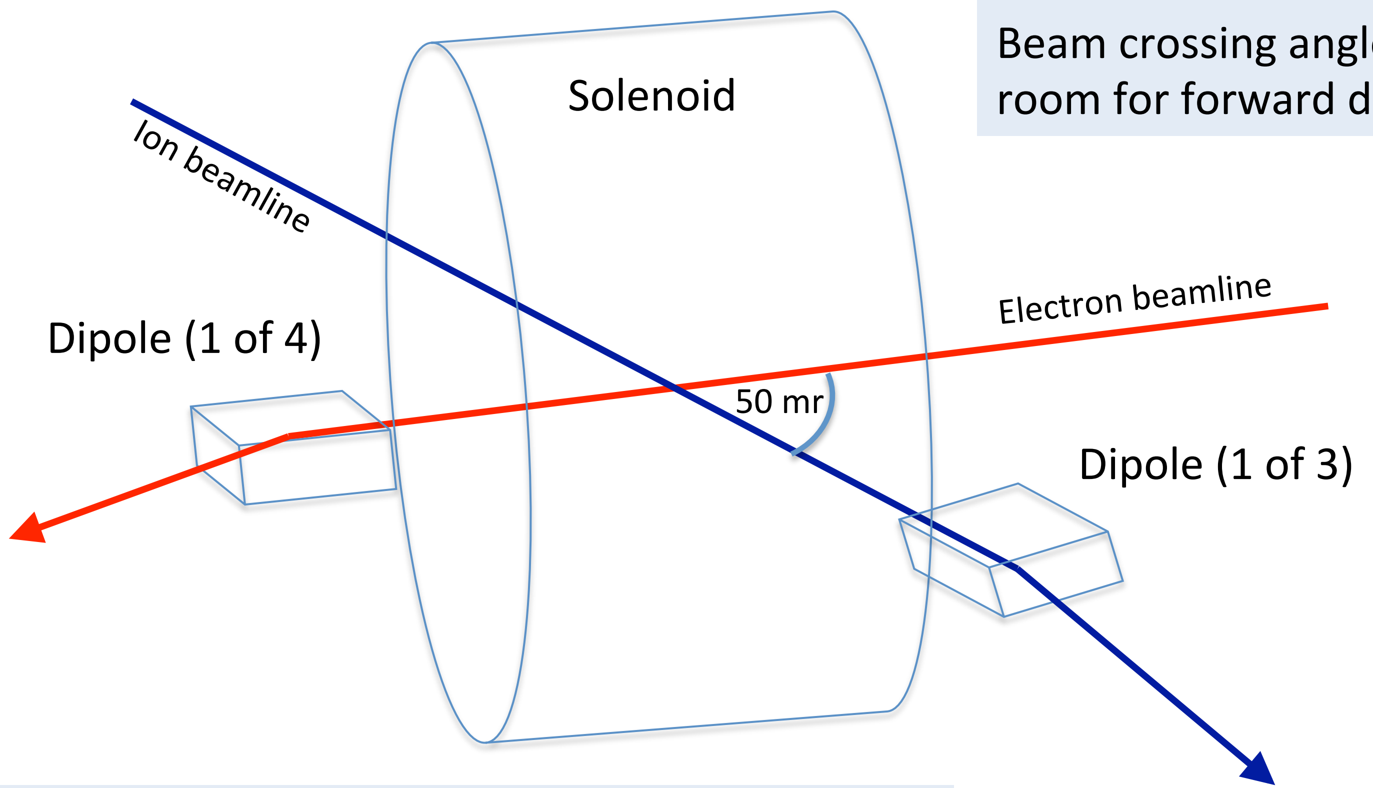


$P_t/P_{beam} <\sim 10^{-3}$

P_t wrt scattering plane.
+ particle ID

Interaction Region Concept

NOT TO SCALE!

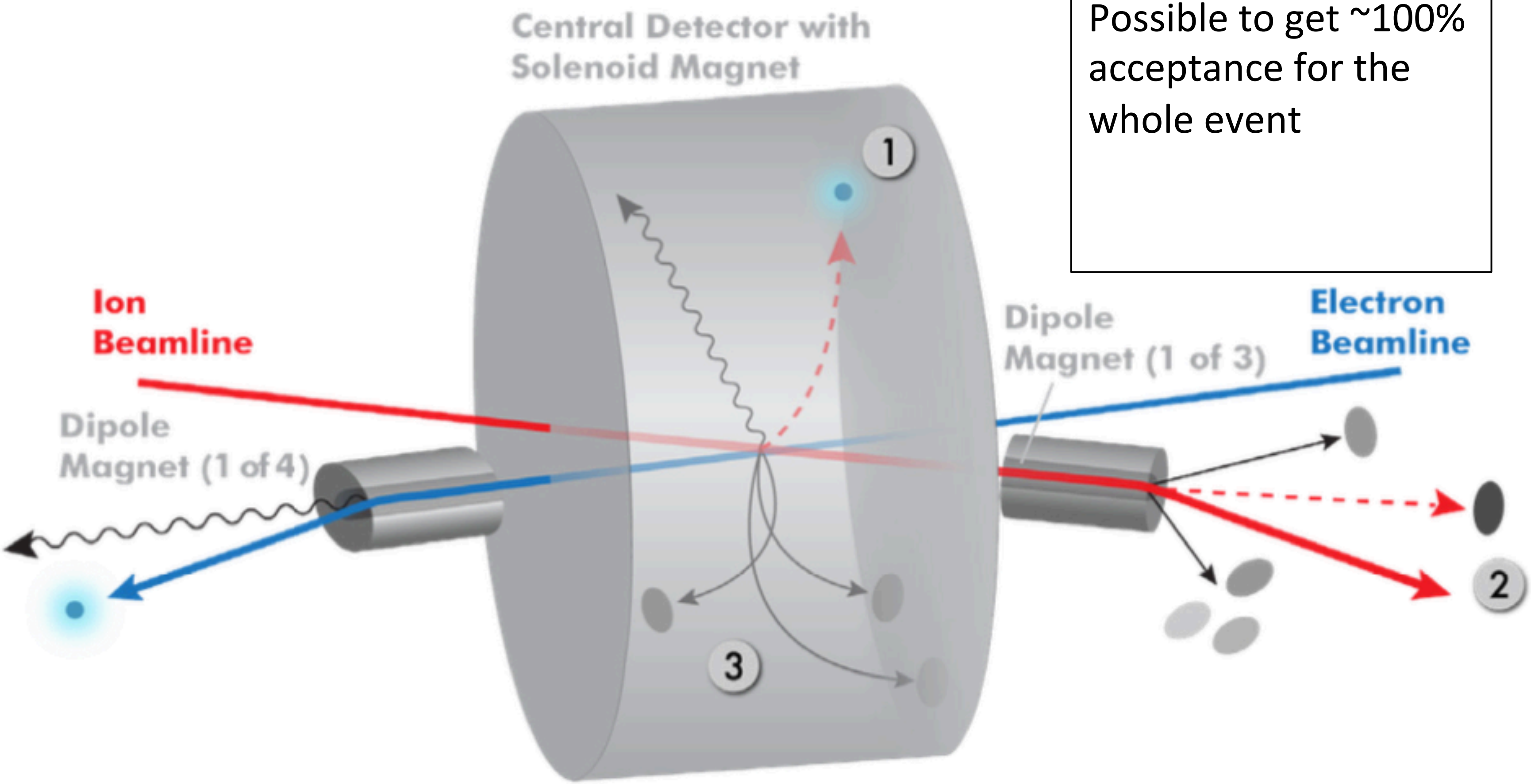


Beam crossing angle creates room for forward dipoles

Dipoles analyze the forward particles
and create space for detectors in the forward direction

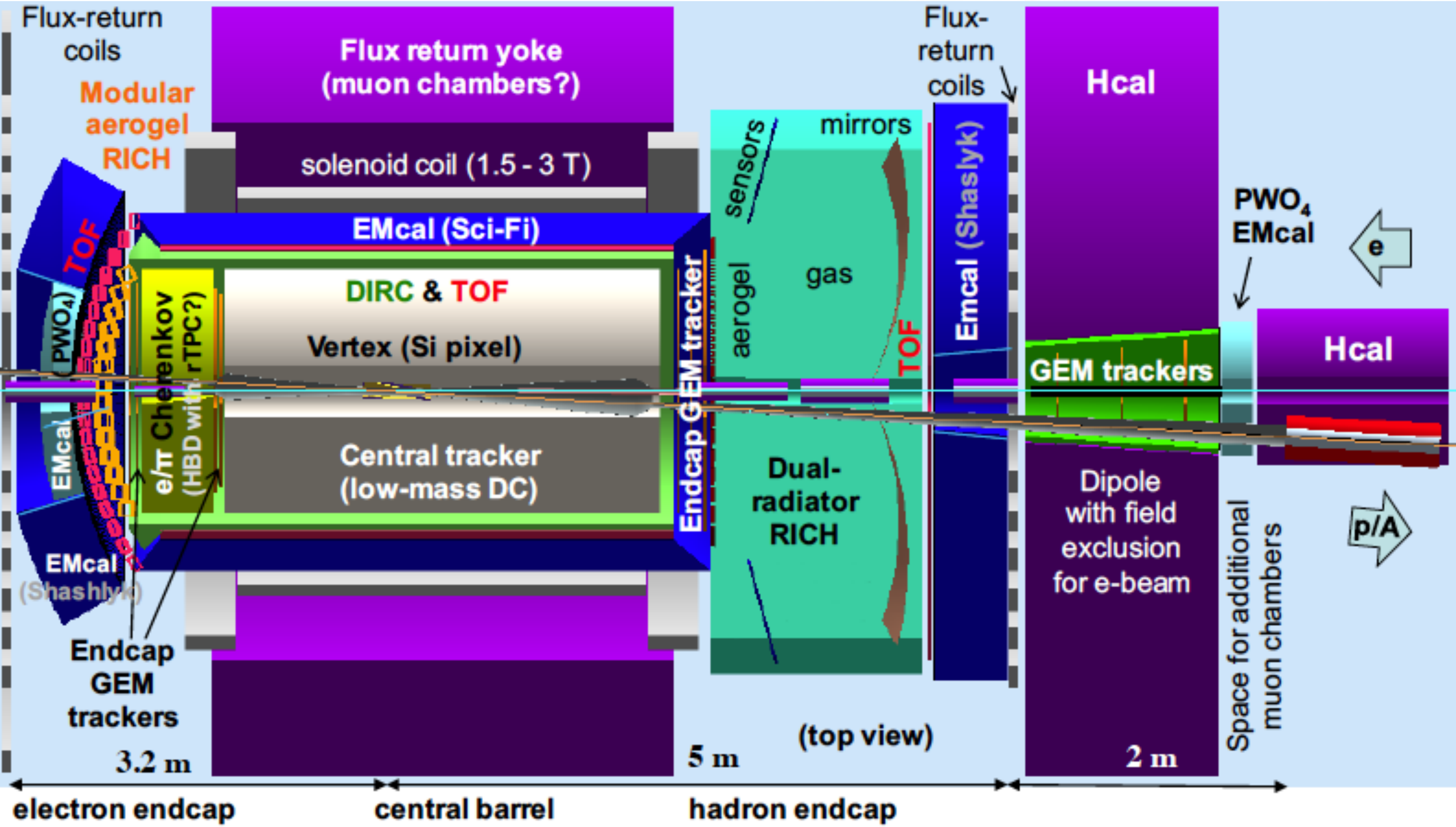
Interaction Region Concept

Possible to get ~100% acceptance for the whole event



Total acceptance detector (and IR)

Current JLEIC Concept



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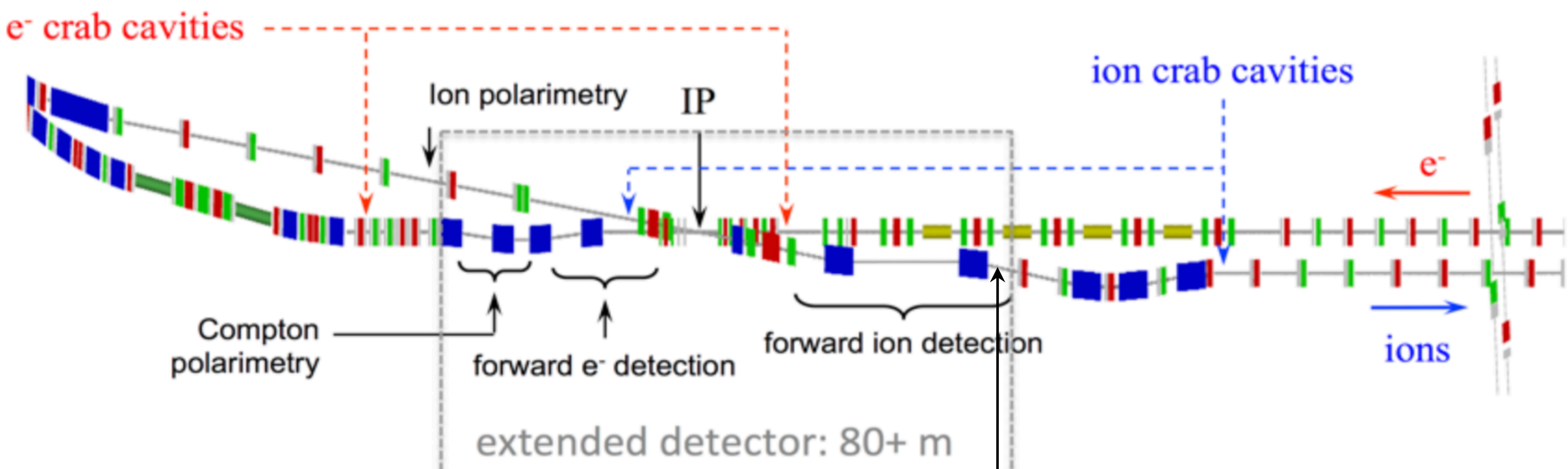
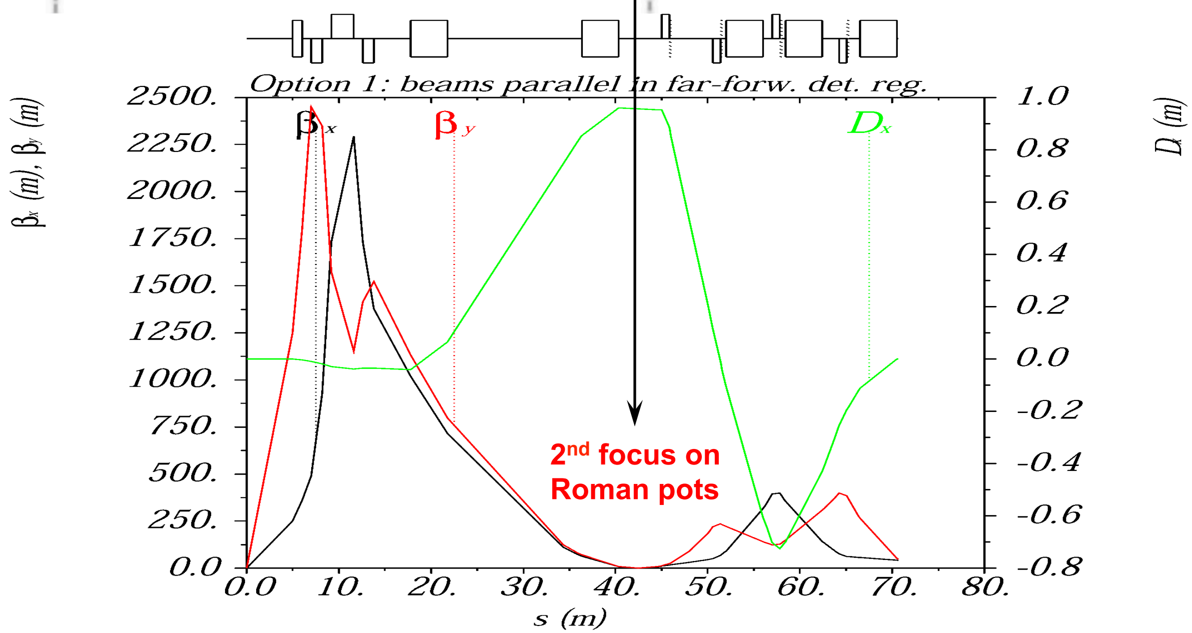
Ion optics for near-beam detection



- A large ***dispersion*** at the detection point separates scattered (off-momentum) particles from the beam.
- A ***second focus*** and small emittance (cooling) allows moving detectors closer to the beam



JLEIC IR and Detector Layout

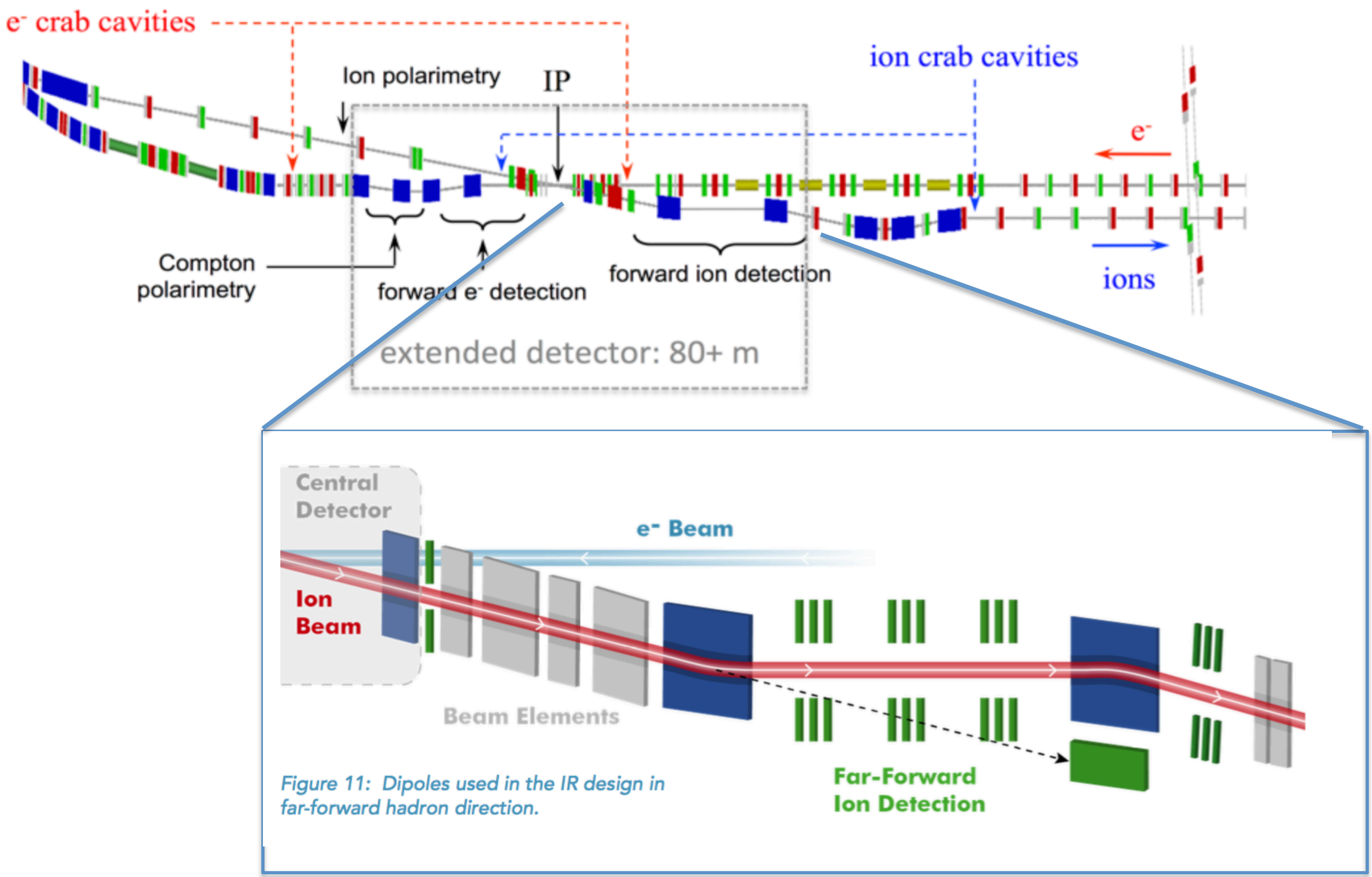


Figure 11: Dipoles used in the IR design in far-forward hadron direction.

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EIC forward detection requirements

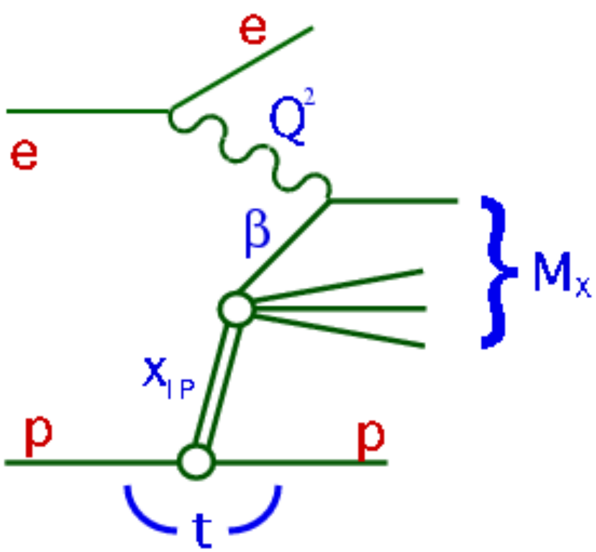
- Good acceptance for recoil nucleons (rigidity close to beam)
  - **Diffractive processes on nucleon, coherent nuclear reactions**
  - Small beam size at detection point (to get close to the beam)
    Secondary focus on roman pots, small beam emmittance (cooling)
  - Large dispersion (to separate scattered particles from the beam)

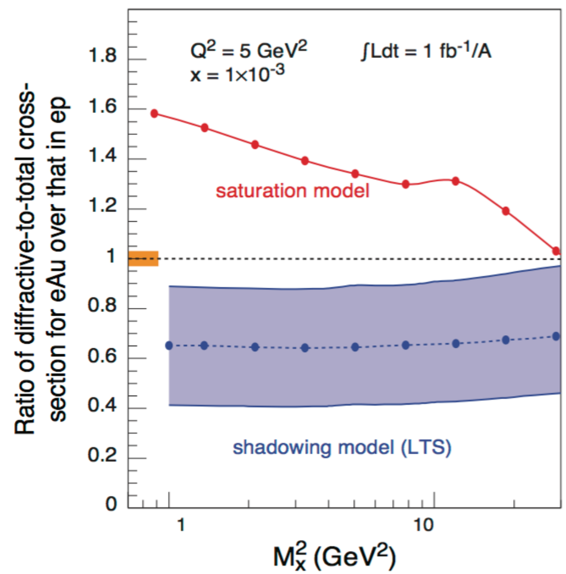
- Good acceptance for fragments (rigidity different than beam)
  - **Tagging in light and heavy nuclei, nuclear diffraction**
  - Large magnet apertures (low gradients)
  - Detection at several points along a long, aperture-free drift region

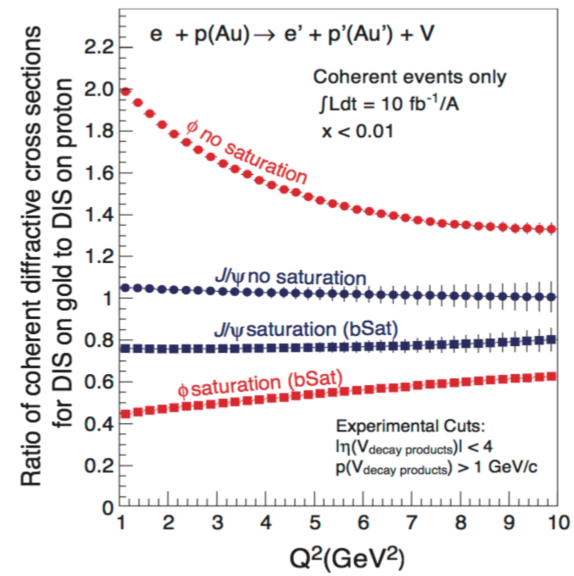
- Good momentum- and angular resolution
  - **Free neutron structure through spectator tagging, imaging**
  - Both in roman pots and fixed detectors

An Example: Diffractive DIS

Signature for Saturation (among other things)







Identify the scattered proton: distinguish from proton dissociation
Measure $\mathbf{X_L = E_p'/E_p}$, and $\mathbf{P_t}$ (or **t**) (equiv. to measuring M_x)

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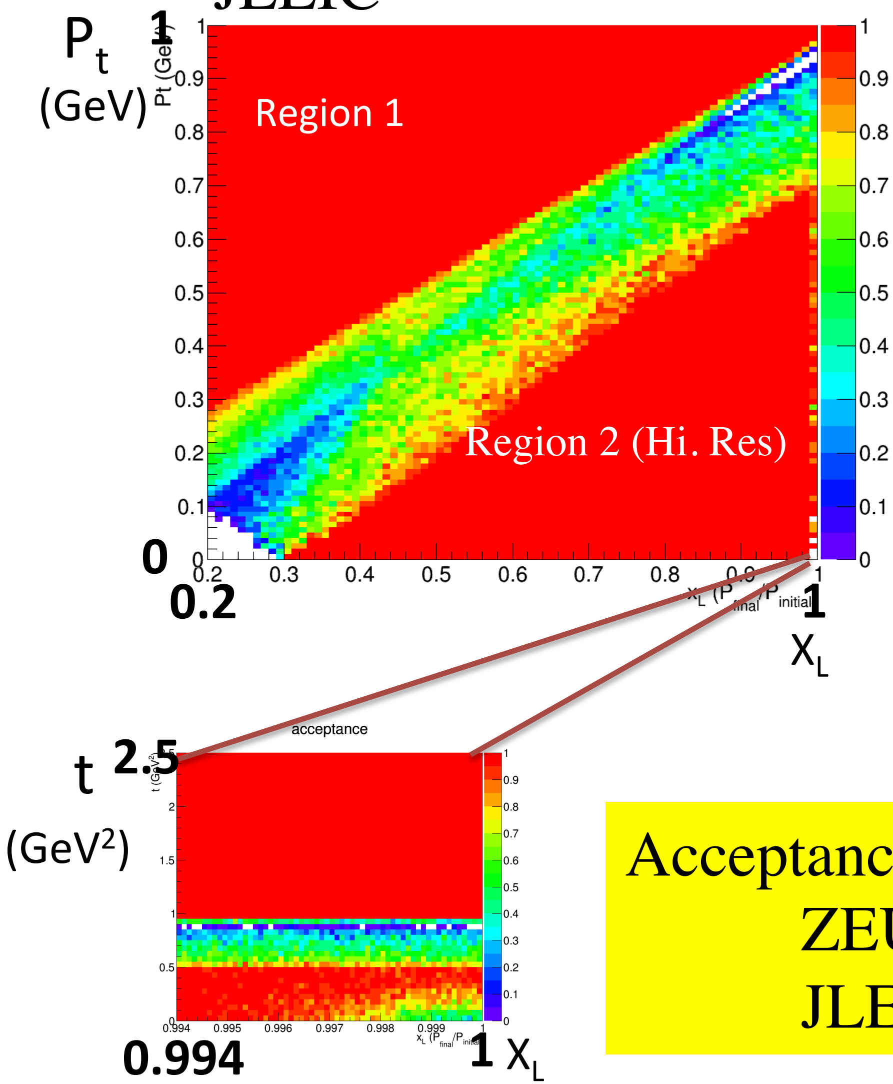
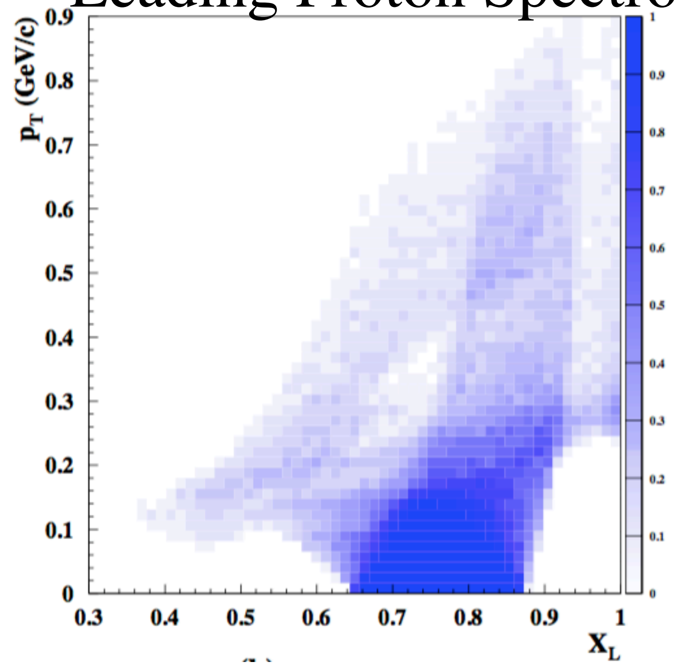
Acceptance for p’ in DDIS

JLEIC



ZEUS

Leading Proton Spectrometer



Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

JLEIC: ~100%

JLEIC Detector and IR Document

JLEIC Documentation Series – 001

Jefferson Lab
Electron-Ion Collider (JLEIC):

An Introduction to the Interaction Region and Detector Design

Authored by the JLEIC Detector and Interaction Region Study Group

Jefferson Lab Electron-Ion Collider is a proposed realization of the Electron-Ion Collider (EIC) [1]. The EIC has been chosen as the highest priority new construction for Nuclear Physics in the US [2]. We discuss the main drivers for design of the JLEIC interaction region and the detectors, and the layout that was developed in response to these drivers.

[1] A. Accardi et al., *Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all*, JLAB-PHY-12-1652, 2012.
[2] A. Aprahamian et al., *Reaching for the horizon: The 2015 long range plan for nuclear science*, 2015.

Jefferson Lab JLEIC

Can be found at the JLEIC Public Wiki page at: https://eic.jlab.org/wiki

This a short 9-page general introduction for people new to JLEIC.

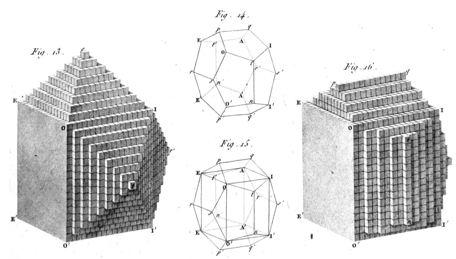
More specific and detailed documents to follow.

Also working on a document server implementation.

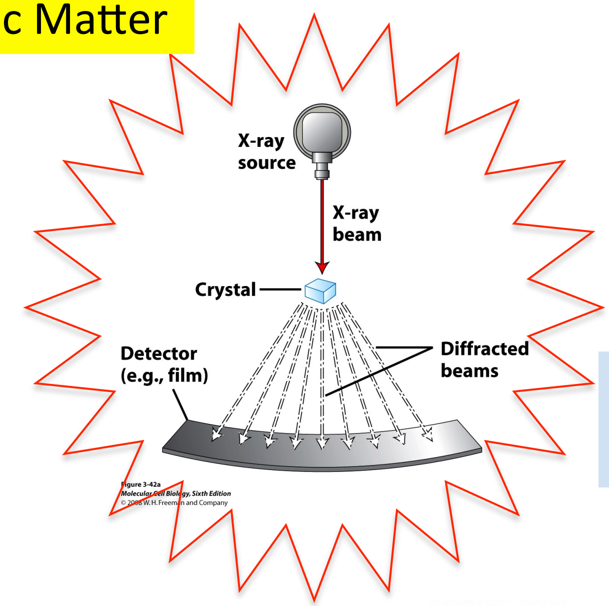
EPILOGUE

New Probes and New Science

Example: Structure of Atomic Matter

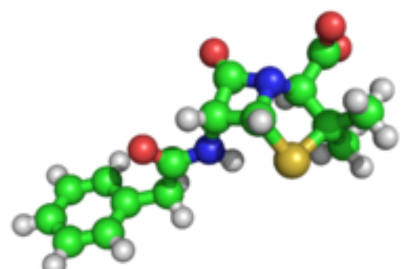


Crystal Structure: 1801

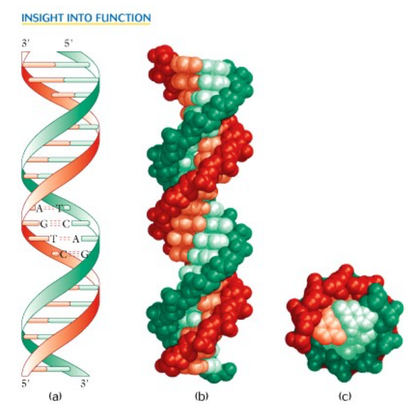


Advent of X-ray Diff. 1912

Probe with the right scale!



3D structure of penicillin: 1945

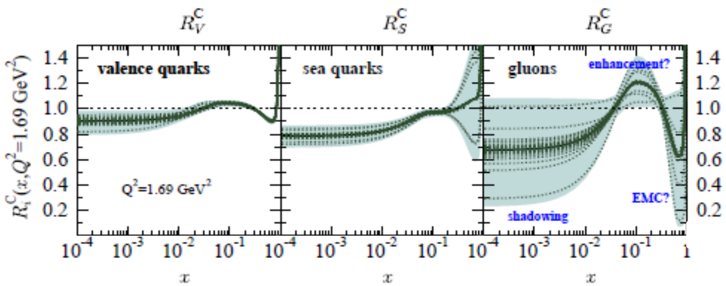


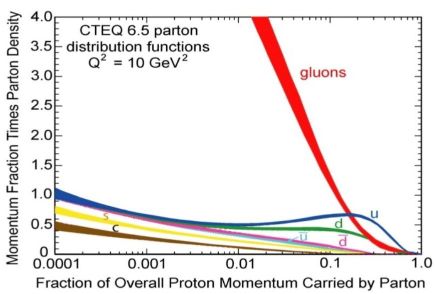
Double Helix: 1953

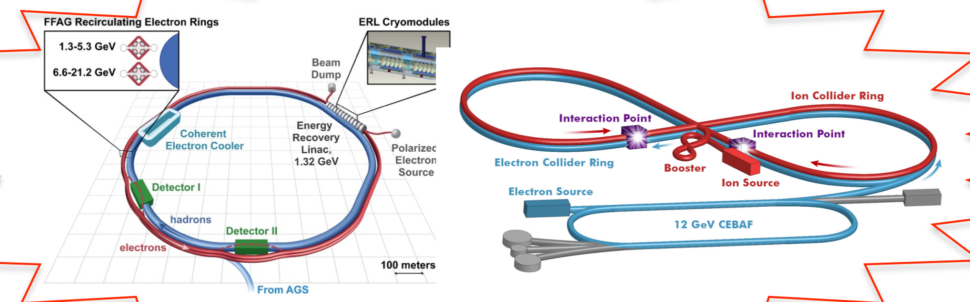
Precise understanding of structure leads to rich new sciences

New Probe for Nuclear Science

2016

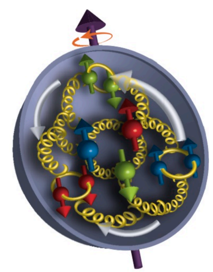


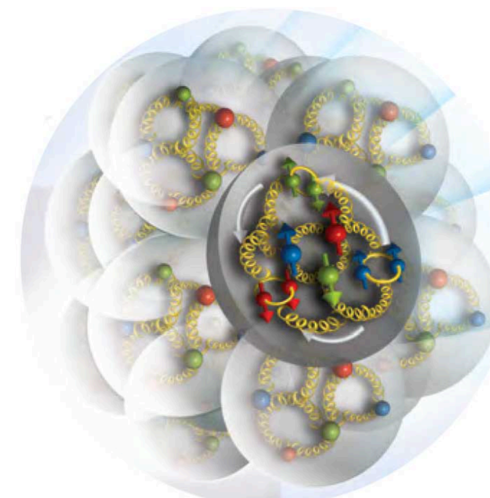




Advent of EIC: ~2027

Probe with the right scale!





Precise understanding of structure and dynamics: dawn of new science

Jefferson Lab

Conclusion

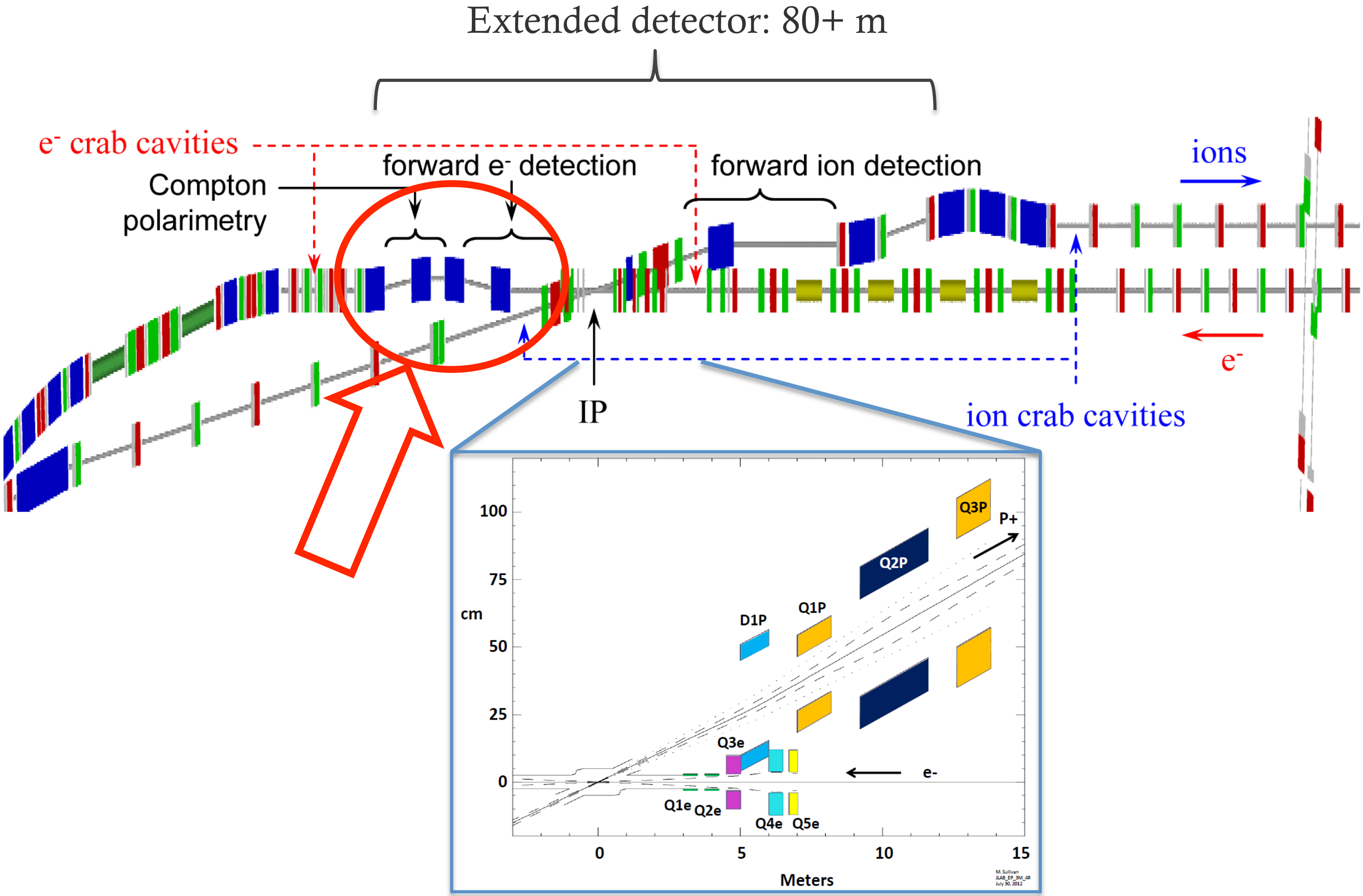
- EIC Program aim: Revolutionize the understanding of nucleon and nuclear structure and associated dynamics. Explore new states of QCD.
- Outstanding questions raised both by the science at RHIC/HERA/LHC and at HERMES/COMPASS/Jefferson Lab—as well as the advance in Theory--led to the science and the EIC proposal.
- For the first time, EIC will enable us to study the nucleon and the nucleus at the scale of quarks and gluons, over (arguably) all of the kinematic range that are relevant.
- JLEIC Baseline parameters are designed to enable all of the physics in the whitepaper on Day 1.
- JLEIC IR and Detector concepts are designed to best enable the physics of the whitepaper—and made in close collaboration with the Accelerator design.
- I believe EIC will be a start of something qualitative new in nuclear physics.
- In the next decades, with the advent of EIC, nuclear science will grow and become more central to the sciences. We're just getting started!

The future of science demands an Electron Ion Collider

BACKUP

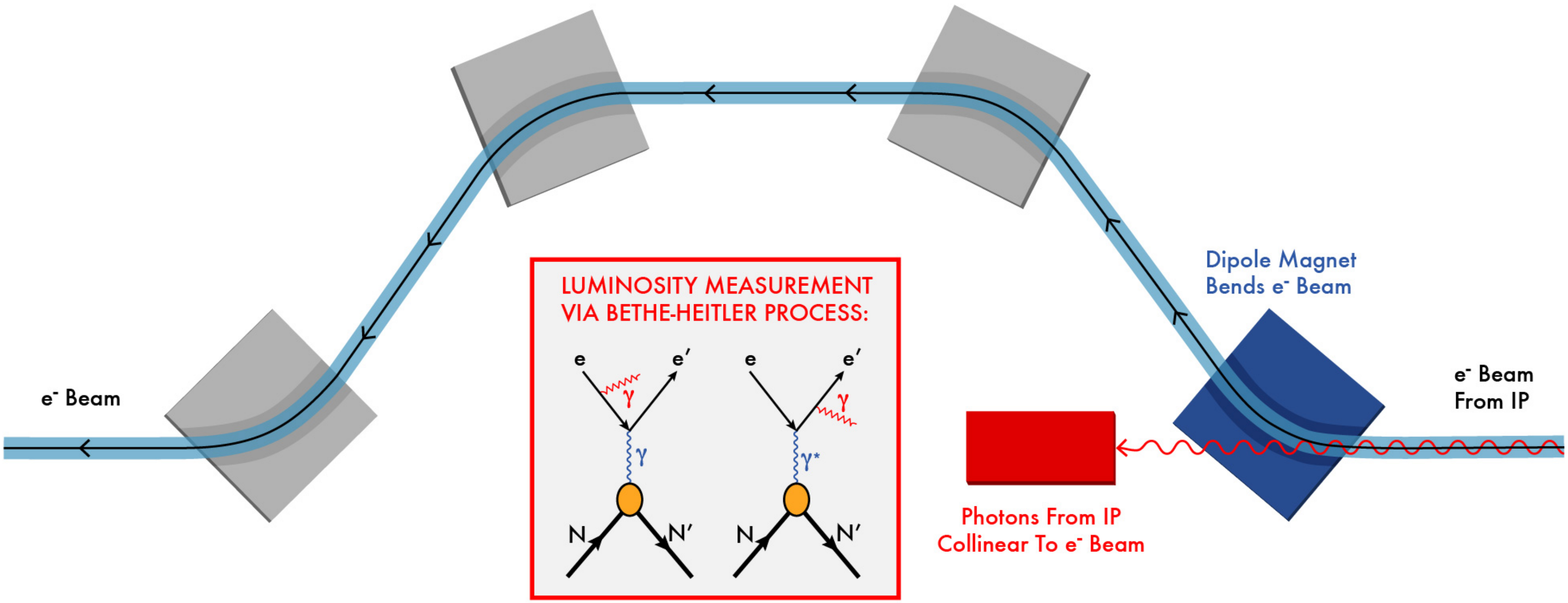
ELECTRON-BEAM DIRECTION

Chicane for Electron Forward Area

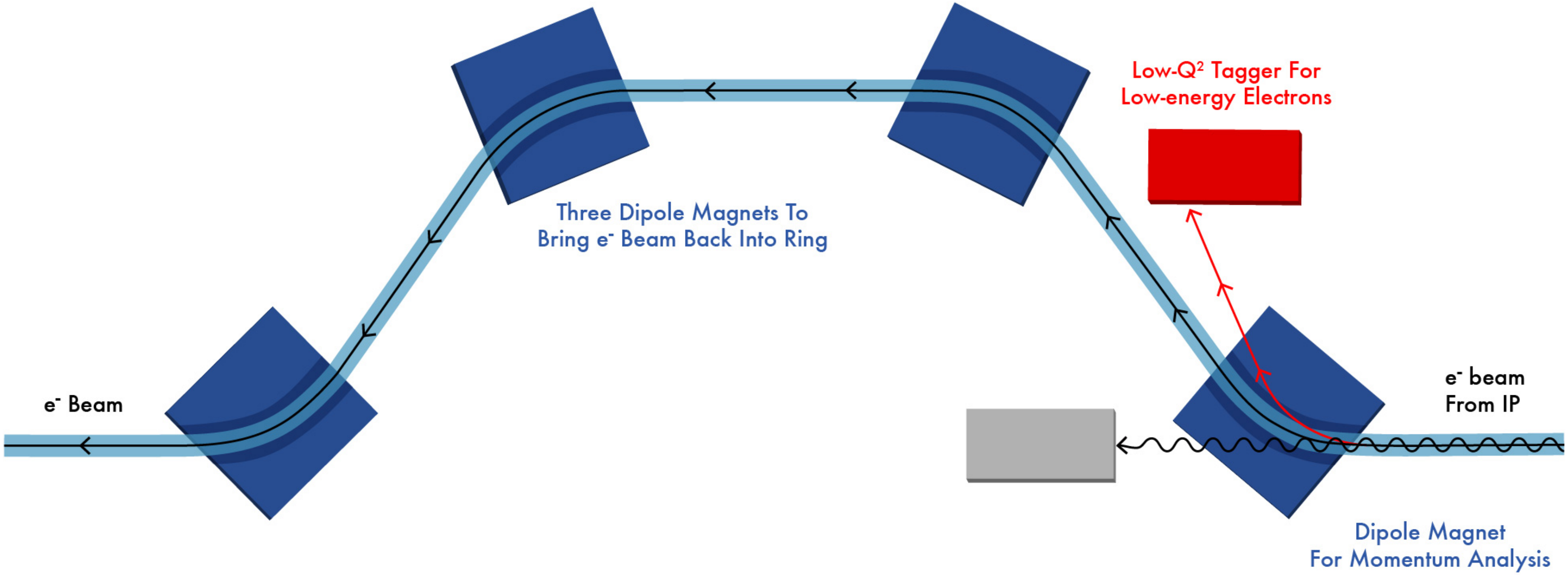


Luminosity Measurement

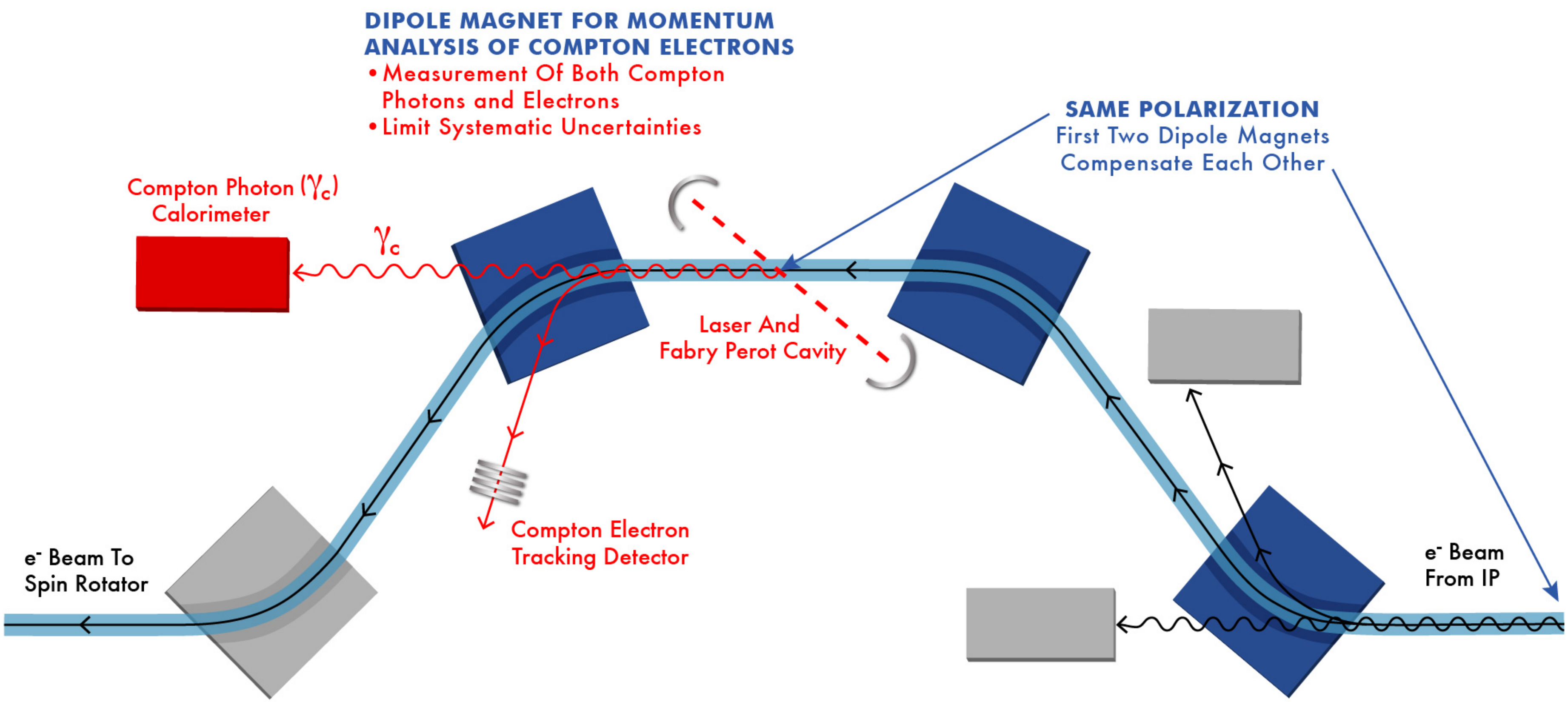
Use Bethe-Heitler process to monitor luminosity: same as HERA



Low Q^2 Tagger

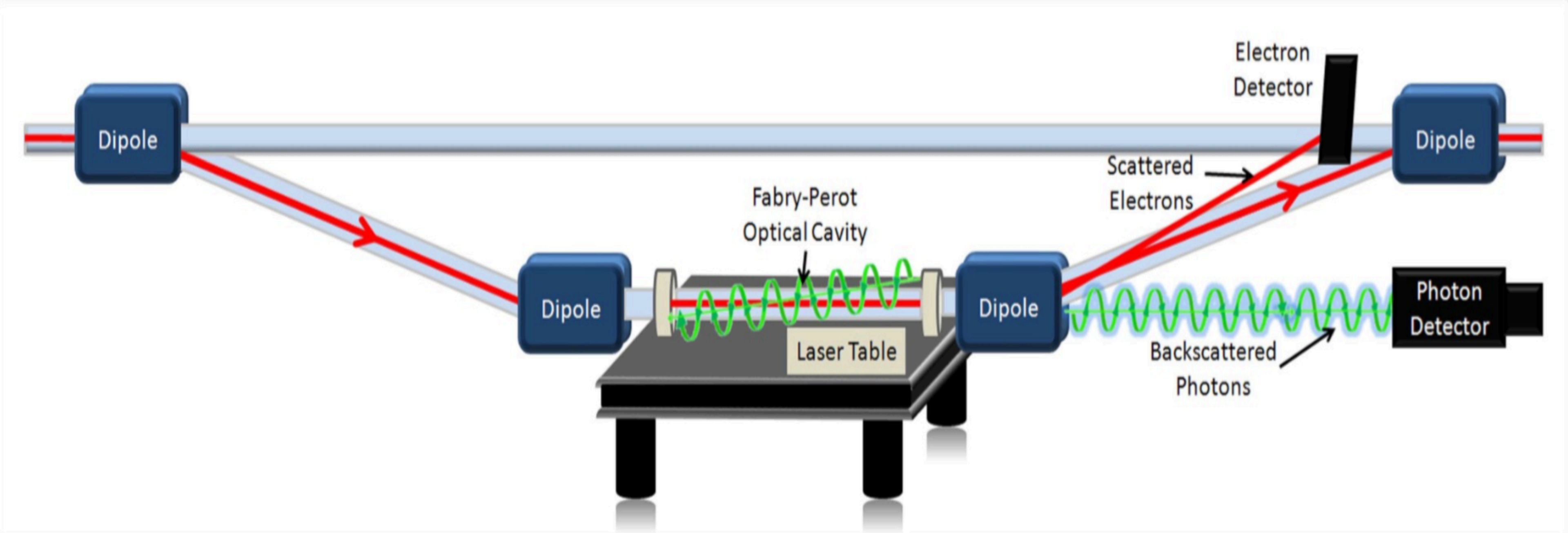


Polarization Measurement



Note the off-momentum electrons from IP does not enter the Compton tracker for polarimetry.

Compton Polarimetry



Existing Polarimeter in Hall C at JLab: Achieved 1% Precision

JLEIC performance without bunched beam cooling at collision

JLEIC strategy: **DC cooler** in Booster for emittance reduction

Bunched beam cooler at collision to cancel/reduce IBS

Evolution from "strong" to "weak" bb-cooling:

Cooling		**Strong (with a circulator ring)**		**Weak (without a circulator ring)**	
		p	*e*	*p*	*e*
Beam energy	GeV	100	5	100	5
Collision frequency	MHz	**749.5**		**476**	
Particles per bunch	10^{10}	0.417	2.33	0.66	3.9
Beam current	A	0.5	2.8	**0.5**	3
Polarization	%	> 70%	> 70%	>70%	>70%
Bunch length, RMS	cm	1	1.2	1	1.2
Norm. emitt., vert./horz.	μm	**0.35 / 0.035**	53.5 / 5.35	**1 / 0.5**	144 / 72
Horizontal and vertical β^*	cm	20 / 2	12 / 1.2	4/2	2.6/1.3
Vert. beam-beam param.		0.015	0.031	0.006	0.014
Laslett tune-shift		0.033	Small	0.01	small
Detector space, up/down	m	3.6 / 7	3.2 / 3	3.6 / 7	3.2 / 3
Hourglass(HG) reduction		0.83		0.88	
Lumi./IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	**7.4**		**4.6**	

2012 MEIC Design Report

2015 MEIC Design Report